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TEST REPORT

HYDROGEN EMBRITTLEMENT TESTS OF PRESSURIZED CYLINDRICAL AND TENSILE SPECIMENS INCLUDING CONVENTIONAL TENSILE TESTS ON ASTM A-302-B STEEL, NICKEL MODIFIED

Beckham 5-8761

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ASTM A-302-B STEEL, NICKEL MODIFIED

ABSTRACT

This report presents the results of burst test on thin wall test cylinders and tensile specimens fabricated from an ASTM pressure vessel steel A-302-B, nickel modified.

1. Pressurized thin wall cylinders.

The test specimens were cut from scraps of a 3.25 inch thick rolled sheet of the A-302-B steel, nickel modified, used to fabricate hydrogen gas storage vessels. The longitudinal axis of the cylindrical test specimens was perpendicular to the roll direction of the material.

The following tests were conducted.

a. Twelve (12) reference specimens were ruptured using nitrogen gas at a pressurization rate of approximately 10,000 psig per second.

b. Twelve (12) specimens were pressurized to 6,000 psig with helium gas, stored for 24 hours, and ruptured using nitrogen gas at a pressurization rate of approximately 10,000 psig per second.

c. Twelve (12) specimens were pressurized to 6,000 psig with hydrogen gas, stored for 24 hours, and ruptured using nitrogen gas at a pressurization rate of approximately 10,000 psig per second.

d. Twelve (12) specimens were pressurized to 10,000 psig with helium gas, stored for 720 hours, and ruptured using nitrogen gas at a pressurization rate of approximately 10,000 psig per second.

e. Twelve (12) specimens were pressurized to 10,000 psig with hydrogen gas, stored for 720 hours, and ruptured using nitrogen gas at a pressurization rate of approximately 10,000 psig per second.

The test results indicated a small net reduction in ultimate strength for hydrogen charged thin wall specimens (A-302B material) as compared to those charged with helium gas.

2. Pressurized Tensile Specimens.

The test specimens were fabricated from A-302-B steel, nickel modified. The longitudinal axis of the specimens was parallel to the mill roll direction of the material.

The following tests were conducted:

a. Thirty five (35) specimens were stored in a 6000 psig helium atmosphere at stresses of 50, 75, 90, 100, 110, 120 and 130 ksi for 24 hours and then failed in tension by increasing the helium pressure. Five (5) specimens were tested in a similar manner with nitrogen.

b. Forty two (42) specimens were stored in a 6000 psig hydrogen atmosphere at stresses of 50, 75, 90, 100, 110, 120 and 130 ksi for 24 hours, and then failed in tension by increasing hydrogen pressure.

c. Five (5) specimens were stored at a stress of 110 ksi for one hour while exposed to MIL-H-5606 hydraulic fluid at 6000 psig. The specimens were failed in tension by increasing the hydraulic pressure.

The test results indicated that hydrogen embrittlement occurs at or near the yield point, probably simultaneously with yielding.

3. Tensile tests on A-302-B steel, nickel modified

Data was obtained on the tensile strength of A-302-B steel, nickel modified in the direction of mill roll and each of two axes mutually perpendicular to the direction of mill roll. Fifteen specimens were tested in each axis except the axis vertically perpendicular to the direction of mill roll. Nine specimens were tested in this axis.

FOREWORD

This document has been prepared for the National Aeronautics and Space Administration, Kennedy Space Center, Launch Support Equipment Engineering Division, Launch Equipment Reliability Office, Kennedy Space Center, Florida. This testing was authorized by Technical Directive Number KSC-91 of Contract NAS10-1360.

The test was conducted and the report prepared by the Test Department, of Brown Engineering Company, Inc., Huntsville, Alabama. This is Brown Engineering Company Report Number 415.

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I. SUMMARY

A. Pressurized Thin Wall Cylinders

1. Sixty (60) test specimens fabricated from A-302-B steel, nickel modified were tested. The specimens were thin wall pressure cylinders with the longitudinal axis of the specimens being perpendicular to the mill roll direction of the parent material. The specimens were stored with GH_2 or GHe at pressures of 6, 000 psig and 10, 000 psig for 24 hours and 720 hours and then pressurized until failure with GN_2.

2. An average reduction of strength, which ranged from 1.9% to 7.4%, was found for hydrogen charged specimens as compared to those charged with GHe. However, there was considerably more difference in strength between individual specimens tested at a given set of conditions than there was between the average strengths of the GH_2 and GHe charged specimens. The average tensile strengths were higher for specimens stored, with both GHe and GH_2, for 720 hours than for those stored for 24 hours. This may possibly be attributed to strain hardening of the metal. The test data are summarized in Summary Table 1.

B. Pressurized Tensile Tests

1. Ninety(90) specimens fabricated from A-302-B steel, nickel modified were tested. The longitudinal axis of the tensile specimens were parallel to the mill roll direction of the parent material. The specimens were stored for 24 hours at tensions ranging from 50, 000 psi to 130, 000 psi, in an atmosphere of GH_2 or GHe at 6000 psig. At the conclusion of the 24 hour storage period the specimen was burst in the presence of the gaseous atmosphere.

2. The ultimate stress averages were erratic. There was no definite trend of hydrogen embrittlement effect on ultimate stress.

3. The change of net average reduction in area of the GH_2 specimens as compared to the GHe specimens ranged from -3. 6 % to - 18. 2%. All reduction in area averages indicated embrittlement effects from hydrogen exposure.

4. The change of the average elongation of the GH_2 specimens as compared to the GHe specimens ranged from -10. 2% to +1. 2%. All groups of specimens, except those stored at 120, 000 psi stress, had a lower average elongation for the GH_2 specimens than for the GHe specimens.

5. Metallographic studies were made on specimens tested with

GH_2, GHe, GN_2, MIL-H-5606 hydraulic fluid and specimens stored at 120,000 psi stress in a GH_2 atmosphere, but not burst. The results of this study are presented in Appendix B.

Specimens tested to failure with hydrogen exhibited secondary cracking in the necked area. This phenomenon is typical of hydrogen embrittlement. All other specimens, including GH_2 specimens not tested to failure but stored for 24 hours in the yield range, did not exhibit secondary cracking.

6. The test data are summarized in Summary Table 2.

C. Tensile Tests

1. Thirty-eight (38) specimens fabricated from A-302-B steel, nickel modified were tested. The specimens were fabricated for testing parallel to the direction of roll during plate formation and for each of two axes mutually perpendicular to the direction of roll.

2. The test data are summarized in Summary Table 3.

D. History of Failures

From NASA files, a history of failures of high pressure GH_2 vessels is presented in Appendix D.

II. CONCLUSIONS AND RECOMMENDATIONS

1. These tests indicated that hydrogen embrittlement occurs only at or near the yield point. Specimens stored at 120,000 psi stress (in the yield stress range) for 24 hours with gaseous hydrogen and not tested to failure did not exhibit the secondary cracking peculiar to hydrogen embrittlement, while those tested to failure did exhibit secondary cracking. Welds or other sections of pressure vessels where concentrated stresses near the yield point of the material occur are possible locations for hydrogen embrittlement failure.

2. Temperature has a decided effect on hydrogen embrittlement. Further investigation is necessary to determine fully this effect.

Summary Table 1. Tests on Pressurized Thin Wall Cylinders

Test Media	Pressure (psig)	Storage Time (hours)	Average Ultimate Stress (psi)	Net Reduction of Strength of GH_2 Specimens as compared to GHe Specimens (%)
GHe	6, 000	24	108, 469	7. 4
GH_2	6, 000	24	100, 446	
GHe	10, 000	24	112, 534	5. 7
GH_2	10, 000	24	106, 070	
GHe	6, 000	720	120, 609	2. 2
GH_2	6, 000	720	117, 990	
GHe	10, 000	720	120, 532	1. 9
GH_2	10, 000	720	118, 277	

Summary Table 2. Tests on Pressurized Tensile Specimens

Specimen Group	Storage Stress (psi)	Test Media	Average Ultimate Stress (psi)	Average Reduction in Area (%)	Average Elongation (%)	Net Change of GH_2 Specimens as Compared to GHe Specimens (%)		
						Ultimate Stress	Reduction in Area	Elongation
X-2	50	He	120,887	63.4	30.0	-1.9	- 9.3	- 7.7
X-2	50	H_2	118,569	57.5	18.5			
X-3	75	He	125,038	65.4	17.3	+1.5	-15.2	- 4.0
X-3	75	H_2	126,892	55.4	16.6			
X-4	90	He	130,101	64.8	16.0	-1.4	- 9.0	- 1.8
X-4	90	H_2	128,225	59.0	15.7			
X-5	100	He	125,980	65.8	16.2	+4.3	-18.2	- 8.9
X-5	100	H_2	131,455	53.8	14.8			
X-6	110	He	128,147	65.2	16.5	+5.1	- 5.2	-10.2
X-6	110	H_2	134,744	61.9	14.8			
X-7	120	He	135,595	64.8	15.4	-4.7	- 3.6	+ 1.2
X-7	120	H_2	129,284	62.5	15.6			
X-8	*	He	128,245	64.6	15.6	-1.6	- 4.9	- 7.8
X-8	*	H_2	126,225	61.4	14.4			

*These specimens burst before storage.

Summary Table 3. Tensile Tests

Axis	Average Ultimate Stress (psi)	Average Yield Strength at 0.2% Elongation (psi)	Average Reduction in Area (%)	Average Elongation (%)
X	130,090	112,600	60.1	22.1
Y	124,700	108,700	11.8	6.1
Z	127,640	110,800	55.6	20.7

* The X-Axis is in the direction of roll. The Y-Axis is vertical and perpendicular to the direction of roll. The Z-Axis is horizontal and perpendicular to the direction of roll.

SECTION I

INTRODUCTION

A. SCOPE

1. This report presents the tests that were performed to determine if hydrogen embrittlement results from exposing A-302-B steel, nickel modified, to gaseous hydrogen. Also presented are the tensile tests that were performed to yield a stress-strain diagram for the metal. The effects of prolonged exposure were evaluated in the test program, using both gaseous helium and gaseous hydrogen for comparison purposes .

2. The hydrogen embrittlement tests were performed in two (2) phases as follows:

a. Phase 1 - Pressurized Thin Wall Cylinder Specimens:

Sixty (60) test specimens were fabricated from the actual material used for manufacture of pressure vessels (A-302-B steel , nickel modified). The specimens were divided into five (5) groups of twelve (12) each, and identified as A1 through A12, B1 through B12, etc. The ultimate strength determination was made by internal pressurization of the specimen until rupture occurred. The pressure rise rate was recorded graphically.

b: Phase 2 - Pressurized Tensile Specimens:

Eighty-seven (87) test specimens were fabricated from the actual material used for manufacture of pressure vessels (A-302-B steel, nickel modified. The specimens were divided into seven (7) groups, as listed in Figure 1-2, and identified as X-2A through X-2K, X-3A through X-3P, etc. Five (5) specimens made of 4340 steel were tested.

3. The tensile tests were performed with thirty-eight (38) test specimens. The specimens were fabricated from actual material used for manufacture of pressure vessels (A-302-B steel). The specimens were fabricated for testing parallel to the direction of roll during plate formation and for each of two axes mutually perpendicular to the direction of roll. The specimens were numbered as shown in Figure 1-3.

B. ITEM DESCRIPTION

1. Hydrogen Embrittlement Tests

a. The thin wall cylinders were fabricated from A-302-B steel, nickel modified, in accordance with Figure 1-1.

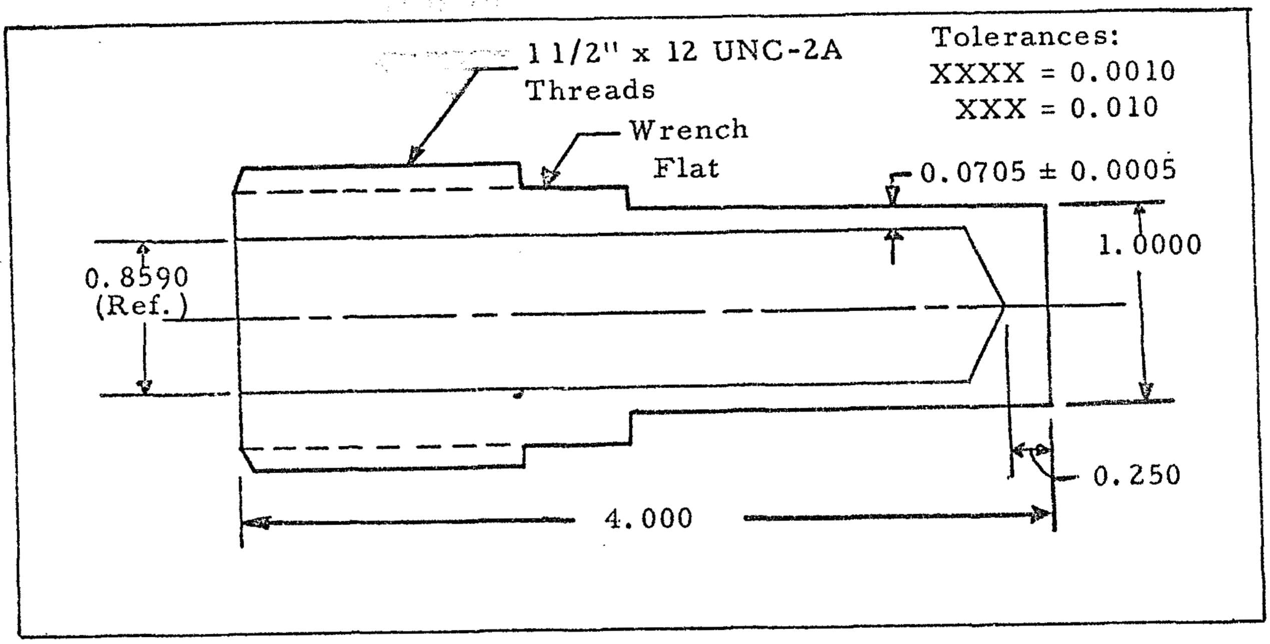
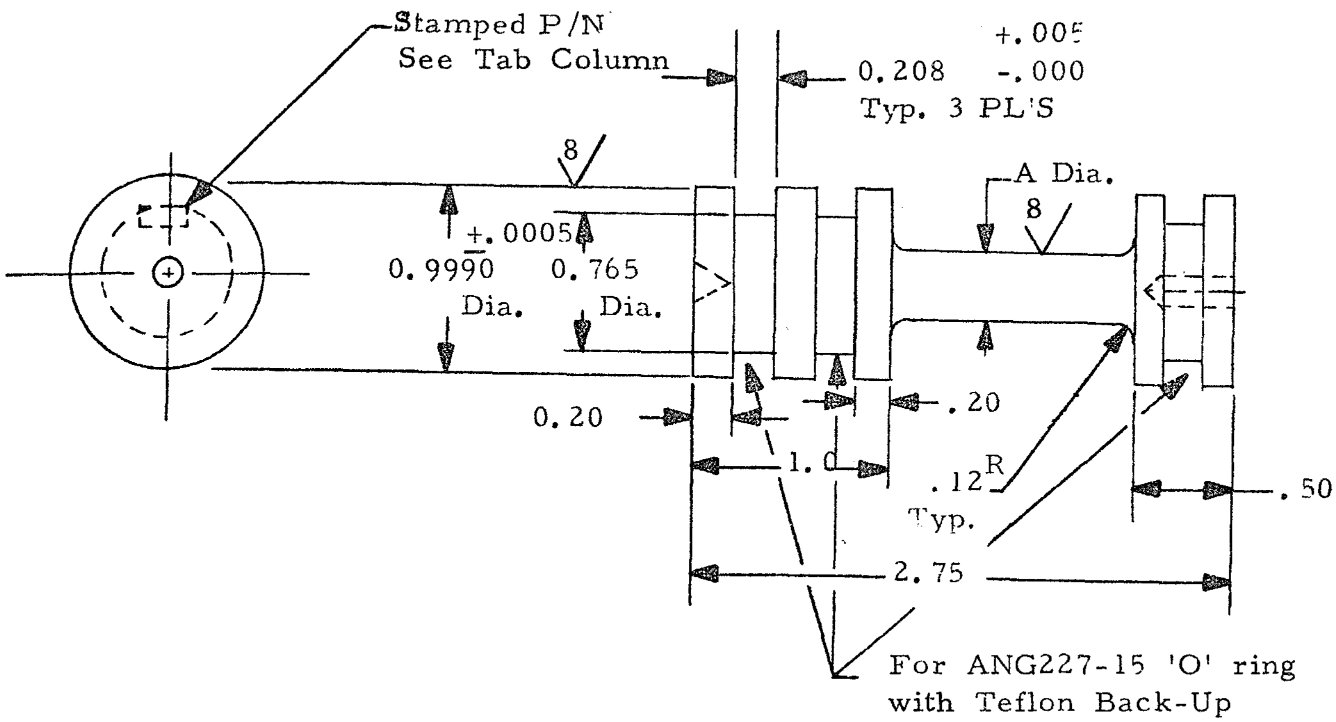


Figure 1-1. Pressurized Cylinder Specimen Dimensions

b. The pressurized tensile specimens were fabricated from A-302-B steel, nickel modified, in accordance with Figure 1-2.

2. Tensile Test

The tensile specimens were fabricated from A-302-B steel, nickel modified, plate as shown in Figures 1-3 and 1-4.



All dimensions are in inches.

X-8 A through K	.211	A302B	11
X-7 A through K	.218	A302B	11
X-6 A through P	.227	A302B	16
X-5 A through K	.238	A302B	11
X-4 A through K	.245	A302B	11
X-3 A through P	.280	A302B	16
X-2 A through K	.329	A302B	11
X-1 A through J	.370	4340	10
Part Number	Dimensions Marked "A"	Material	Number Required

Figure 1-2. Pressurized Tensile Specimen Dimensions

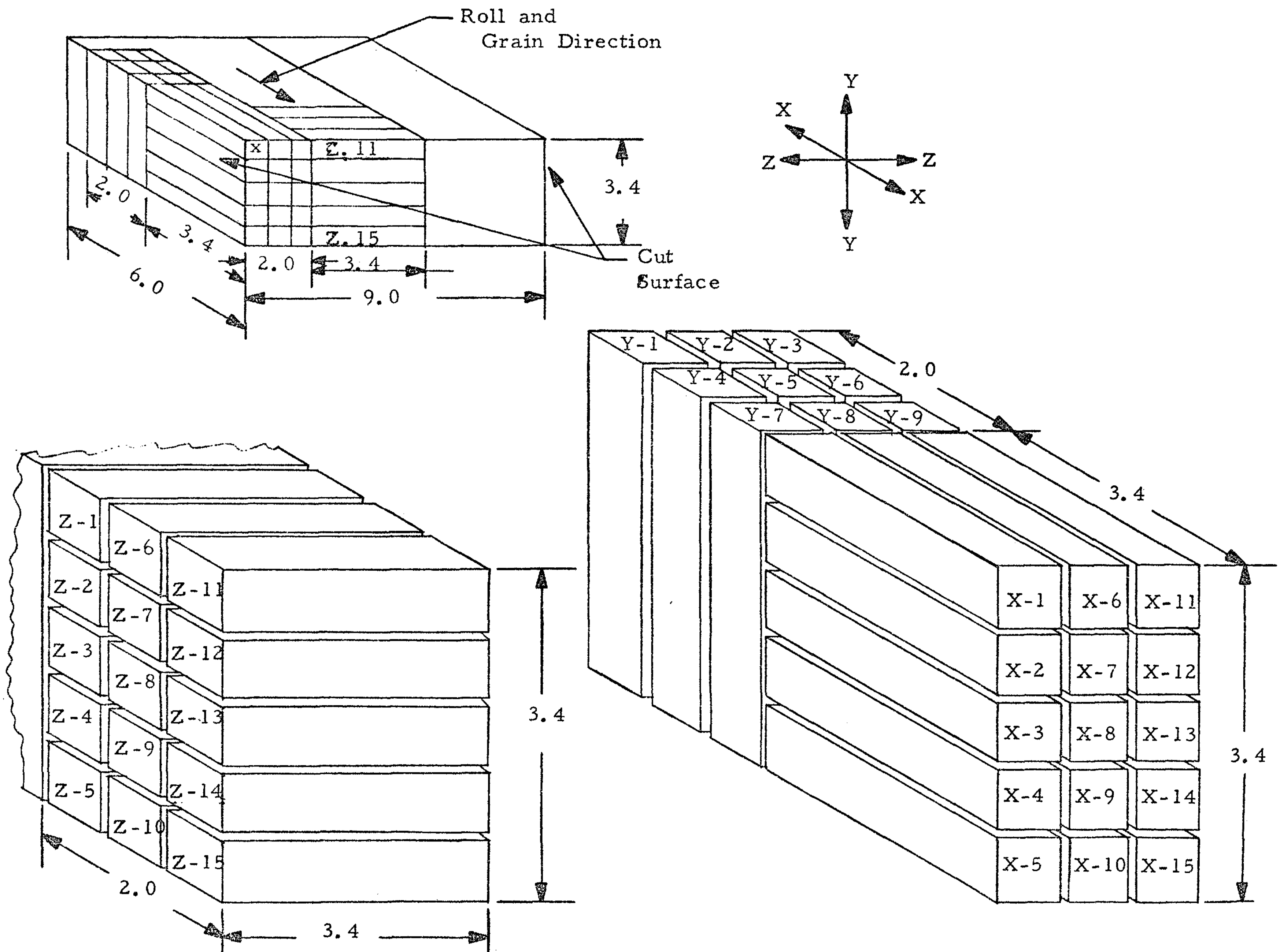


Figure 1-3. Roll and Grain Directions of A302B Steel Plate for Tensile Specimens.

All dimensions are in inches

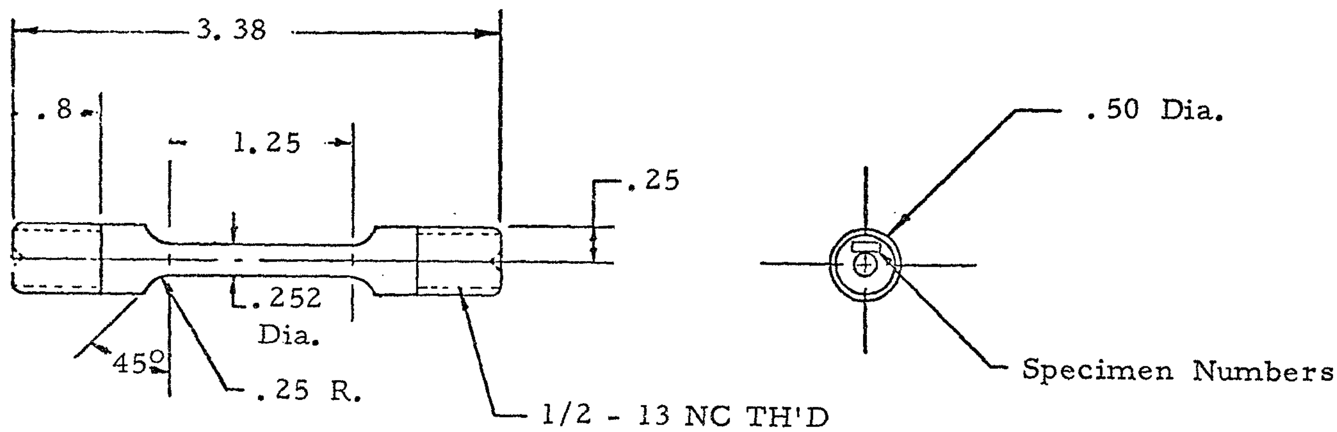


Figure 1-4. Tensile Specimen Dimensions

C. APPLICABLE DOCUMENTS

1. KSC Technical Directive Number KSC-91, dated October 23, 1961.

2. LOC Drawing Number A75M05871, Section P&VE-1, entitled "Vessel, 6000 psig, Gaseous Nitrogen, Helium or Hydrogen Storage, 200 cu. ft., vertically mounted", dated February 14, 1964.

3. Brown Engineering Company Drawing Number 78910052, entitled, "Hydrogen Embrittlement Test Specimen and Fixture".

4. Brown Engineering Company, Inc., Drawing Number MT-30053, entitled, "Plunger", dated August 4, 1965.

5. Fed. Spec. O-T-634 Trichloroethylene.

6. Brown Engineering Company, Inc., Drawing Number MT-20023 entitled, "Tensile Test Specimen", dated June 4, 1965.

7. Brown Engineering Company, Inc., Drawing Number MT-20025, entitled, "Cut Pattern for Tensile Test Specimen", dated June 14, 1965.

SECTION II

INSPECTION AND ASSEMBLY

PRESSURIZED THIN WALL CYLINDERS

A. TEST REQUIREMENTS

1. The specimens and fixture were to be dimensionally inspected for conformance to the requirements of Figure 2-1A.

2. Each specimen was to be identified for future reference.

3. Actual wall thickness of each specimen was to be recorded within $\pm$ 0.0001 inches, at the minimum value.

4. The outside and inside of each specimen was to be checked for concentricity at the area of minimum wall thickness.

5. The specimens were to be assembled in the test fixture as shown in Figure 2-1B. A light coating of KEL-F-90 lubricant was to be applied to the "O"-ring seal prior to installation.

B. TEST PROCEDURE

1. After machining of the specimens and fixtures was complete, a dimensional inspection was performed to insure conformance to the requirements of Figure 2-1A. All applicable data was recorded.

2. Each specimen number was marked on the wrench flats using the designations given in Tables 2-2 through 2-6. Precautions were taken to prevent damaging the specimen surfaces.

3. Eccentricity was measured using a "Talyrond" machine with dual probes. These traces were made at the diameter having the minimum wall thickness as previously determined by dimensional inspection.

4. The specimens were assembled in test fixtures as illustrated in Figure 2-1B. A light coating of KEL-F-90 lubricant was applied on the "O"-ring seal, and mating threads.

All dimensions are in inches.

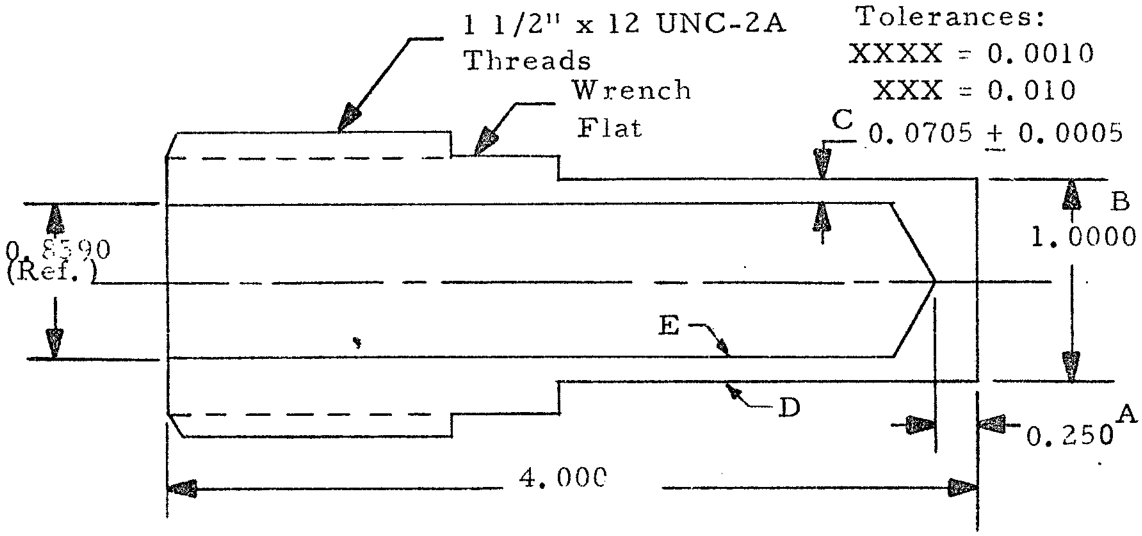


Figure 2-1A. Specimen Dimensions

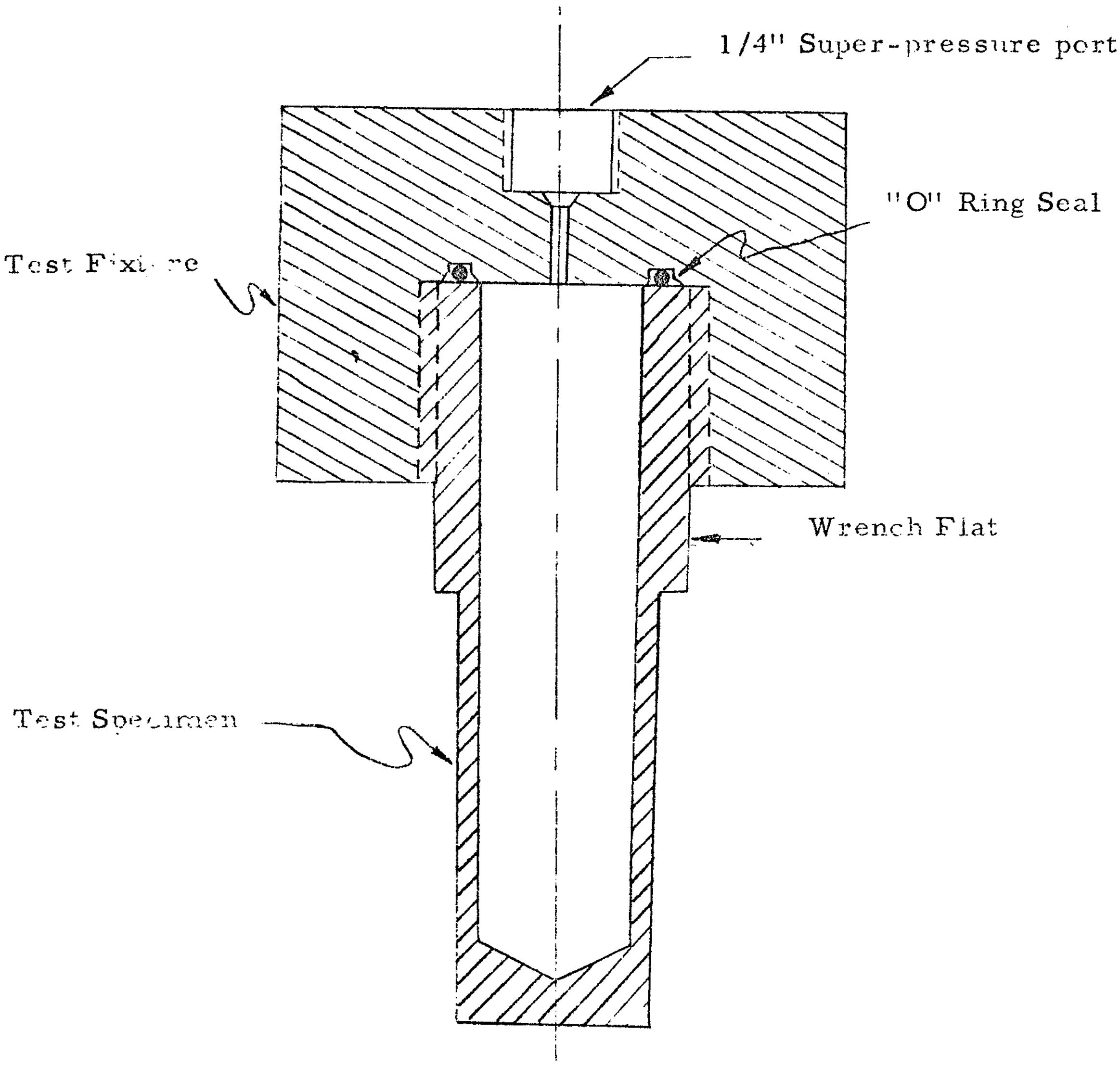


Figure 2-1B. Specimen Installed in Test Fixture.

Table 2-2. Inspection Test Data for Group A Specimens

Speci-men	Thickness A (Inch)	Diameter B (Inch)	Minimum Wall Thickness C (Inch)	Exterior Finish D ***	Interior Finish E ***	*Eccentricity (O.D. & I.D.) (Inch)
A1	.252	1.000	.0707	8	7	**
A2	.215	1.000	.0702	7	8	**
A3	.252	1.000	.0700	7	8	**
A4	.231	1.000	.0710	8	9	**
A5	.236	1.000	.0705	7	7	**
A6	.229	1.000	.0707	6	10	**
A7	.240	1.000	.0705	7	8	**
A8	.235	1.000	.0700	6	7	**
A9	.245	1.000	.0707	7	7	**
A10	.275	1.000	.0706	6.5	8	0.00140
A11	.248	1.000	.0710	7.5	8	0.00015
A12	.253	1.000	.0703	10	7	0.00070

*Eccentricity:

Measured by "Talyrond" curves on specimens @ minimum wall thickness (outside diameter and inside diameter recorded simultaneously).

**"Talyrond" curves were not obtained for these specimens.

*** Roughness number as measured by a surface finish indicator.

Table 2-3. Inspection Test Data for Group B Specimens

Specimen	Thickness A (Inch)	Diameter B (Inch)	Minimum Wall Thickness C (Inch)	Exterior Finish D **	Interior Finish E **	*Eccentricity (O.D. & I.D.) (Inch)
B1	.256	1.0000	.0710	12	7	0.00015
B2	.224	1.0002	.0701	11	6.5	0.00085
B3	.230	1.0001	.0701	12	6.5	0.00140
B4	.243	1.0001	.0707	12.5	7	0.00030
B5	.241	1.0002	.0707	11.5	6.5	0.00025
B6	.248	.9999	.0705	13	7	0.00040
B7	.237	1.0002	.0704	12	7	0.00087
B8	.238	1.0000	.0705	11	6	0.00050
B9	.243	.9998	.0703	12	8	0.00085
B10	.230	.9999	.0707	13	8	0.00060
B11	.256	1.0000	.0706	12	6.5	0.00075
B12	.253	1.0000	.0707	10	8	0.00020

*Eccentricity: Measured by "Talyrond" curves on specimens @ minimum wall thickness (outside diameter and inside diameter recorded simultaneously).

** Roughness number as measured by a surface finish indicator.

Table 2-4. Inspection Test Data for Group C Specimens

Speci-men	Thickness A (Inch)	Diameter B (Inch)	Minimum Wall Thickness C (Inch)	Exterior Finish D **	Interior Finish E **	*Eccentricity (O.D. & I.D.) (Inch)
C1	.2388	1.0005	.0710	8	6	0.00060
C2	.249	1.0003	.0705	8	6.5	0.00020
C3	.236	1.0005	.0700	7	6	0.00040
C4	.246	1.0005	.0700	7.5	6.5	0.00040
C5	.244	1.0007	.0710	7	6	0.00085
C6	.250	1.0005	.0705	7.5	6.5	0.00035
C7	.245	1.0000	.0700	8	7	0.00040
C8	.260	1.0005	.0710	8	7	0.00045
C9	.260	1.0000	.0705	8	7.5	0.00022
C10	.226	1.0050	.0705	7	8	0.00030
C11	.234	1.0004	.0705	7.5	6	0.00015
C12	.250	1.0002	.0700	7.5	8	0.00060

*Eccentricity: Measured by "Talyrond" curves on specimens @ minimum wall thickness (outside diameter and inside diameter recorded simultaneously).

** Roughness number as measured by a surface finish indicator.

Table 2-5. Inspection Test Data for Group D Specimens

Specimen	Thickness A (Inch)	Diameter B (Inch)	Minimum Wall Thickness C (Inch)	Exterior Finish D **	Interior Finish E **	*Eccentricity (O.D. & I.D.) (Inch)
D1	.242	1.000	.0710	8	7	0.00057
D2	.242	1.000	.0705	8	8	0.00060
D3	.246	1.000	.0710	7.5	6.5	0.00030
D4	.249	1.000	.0705	8	6.5	0.00032
D5	.250	1.000	.0700	8	7	0.00034
D6	.234	1.000	.0705	7.5	7	0.00040
D7	.244	1.000	.0710	7.5	7.5	0.00020
D8	.224	1.000	.0700	8	7	0.00072
D9	.229	1.000	.0710	8	6.5	0.00170
D10	.244	1.000	.0705	8	6.5	0.00050
D11	.242	1.000	.0710	8	6.5	0.00070
D12	.244	1.000	.0705	8	7	0.00170

* Eccentricity: Measured by "Talyrond" curves on specimens @ minimum wall thickness (outside diameter and inside diameter recorded simultaneously).

** Roughness number as measured by a surface finish indicator.

Table 2-6. Inspection Test Data for Group E Specimens.

Speci-men	Thickness A (Inch)	Diameter B (Inch)	Minimum Wall Thickness C (Inch)	Exterior Finish D **	Interior Finish E **	*Eccentricity (O.D. & I.D.) (Inch)
E1	2.39	1.0003	.0706	7.5	7	0.00022
E2	.242	1.0000	.0708	8	6.5	0.00085
E3	.219	.9995	.0705	7.5	6.5	0.00087
E4	.244	1.0003	.0705	8	7.5	0.00062
E5	.232	1.0003	.0702	8	7	0.00067
E6	.252	1.0000	.0705	8	7	0.00110
E7	.238	1.0004	.0706	7.5	7.5	0.00050
E8	.231	1.0000	.0705	7.5	7.5	0.00012
E9	.251	1.0000	.0707	8	7	0.00092
E10	.239	1.0005	.0705	7.5	7	0.00055
E11	.232	1.0000	.0703	7	6.5	0.00080
E12	.231	1.0000	.0705	7.5	6.5	0.00140

* Eccentricity: Measured by "Talyrond" curves on specimens @ minimum wall thickness (outside diameter and inside diameter recorded simultaneously).

** Roughness number as measured by a surface finish indicator.

SECTION III

REFERENCE BURST TEST

PRESSURIZED THIN WALL CYLINDERS

A. TEST REQUIREMENTS

1. This test was to be performed with the test specimens installed in a test fixture as shown on Figure 2-2. Specimens A1 through A12 were to be subjected to the test.

2. A calibration pressure run was to be performed to establish a satisfactory pressure rise rate.

3. An energy dissipation unit design was to be evaluated for use in the following phases for personnel protection.

4. The test specimens were to be internally pressurized until rupture occurred utilizing gaseous nitrogen as the test medium.

5. Rate of pressurization and pressure at failure were to be graphically recorded.

B. TEST PROCEDURE

1. The test system was prepared as illustrated on Figure 3-1 using the equipment listed in Table 3-1. A simulated specimen (13) was attached to the test fixture (14). Valves (3) and (9) were opened and all other valves closed.

2. The pressure vessel (4) was pressurized to 22,000 psig using the gas intensifier (1). Valves (3) and (9) were closed. Valve (8) was opened.

3. The recorder (10) was started.

4. The 3-way solenoid valve (11) which supplies air pressure to open the pneumatic operated valve (5) was energized. The solenoid valve (11) was de-energized.

5. The recorder (10) was stopped immediately, and the system vented by gradually opening the vent valve (9). The pressure vessel (4) was recharged to 22,000 psig.

6. The charts were examined to determine the pressure rise rate. Approval of the rise rate was obtained from the KSC test engineer.

7. The fixed orifice line (6) was modified until the pressure rise rate was acceptable.

8. The simulated specimen was removed from the test fixture (14). Specimen A1 was installed in the fixture (14).

9. The pressure vessel (4) was recharged to 22,000 psig, the recorder (10) was started, and step 4 was repeated allowing the specimen to burst.

10. The recorder (10) was stopped immediately after burst.

11. Steps 9 and 10 were repeated for specimens A2 through A12, the pressure output of the pressure transducer (7) was recorded, and the pressure vessel (4) was recharged.

<u>NOTE</u>

> The test setup was always arranged such that the pressure rise rate at the specimen was always at the acceptable level.

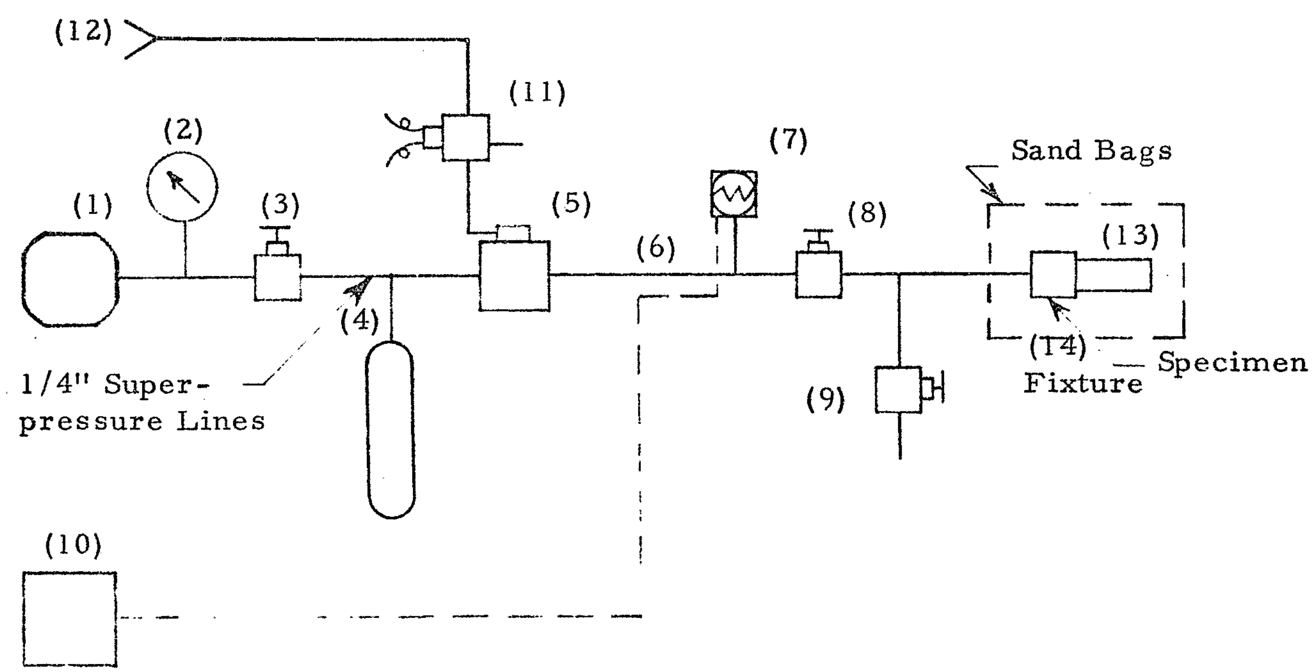


Figure 3-1. Reference Burst Test Setup

Table 3-1. Reference Burst Test Equipment List

Item No.	Item	Manufacturer	Model/ Part No.	Serial No.	Remarks
1.	Intensifier	Aminco	46-4021-M	EE-6668	0-30,000 psig pneumatic
2.	Pressure Gage	Heise	N/A	N/A	30,000 psig range ±0.5% accuracy
3.	Hand Valve	Autoclave	30VM4071	N/A	1/4 inch size, 0-30,000 psig rating
4.	Pressure Vessel	Brown	N/A	N/A	60,000 psig rating
5.	Pneumatic Operated Valve (normally closed)	Autoclave	30VM4071 with "OM" operator	N/A	0.25 in., 60,000 psig rating
6.	Fixed Orifice Line	N/A	N/A	N/A	1/4 inch line, 100,000 psig rating. Length was varied to obtain desired orifice effect.
7.	Pressure Transducer	Strain-Sert	N/A	N/A	0-50,000 psig
8.	Hand Valve	Autoclave	30VM4071	N/A	1/4 inch size, 0-30,000 psig rating
9.	Hand Valve	Autoclave	30VM4071	N/A	1/4 inch size, 0-30,000 psig rating
10.	Recorder	Honeywell	1508	D4R-9167	Oscillograph
11.	3-way Solenoid Valve	Marotta	109	MV-123 B	1/4 inch size, 200 psig rating
12.	Air Supply	N/A	N/A	N/A	150 ± 50 psig

Table 3-1. Reference Burst Test Equipment List (Continued)

Item No.	Item	Manufacturer	Model/ Part No.	Serial No.	Remarks
13.	Specimen	Brown	N/A	N/A	Fabricated
14.	Test Fixture	Brown	N/A	N/A	Fabricated

C. TEST RESULTS

The ultimate stress ranged from 92,507 psi to 119,205 psi. The average ultimate stress was 108,849 psi. A typical specimen failure is shown in Figure 3-2.

D. TEST DATA

The test data is shown in Table 3-2.

Table 3-2. Reference Burst Test Data

Specimen	Burst Pressure (psig)	*Ultimate Strength (psig)	Remarks
A-1	19,500	118,407	
A-2	19,470	119,205	
A-3	19,230	118,127	Failed to burst. Pressure leaked down to 18,500 psig. Pressure was then increased until failure.
A-4	19,500	117,824	
A-5	16,500	100,521	
A-6	18,110	109,966	
A-7	15,850	96,561	
A-8	18,680	114,749	
A-9	16,000	97,154	
A-10	16,820	102,302	
A-11	15,310	92,507	
A-12	18,750	114,607	
Average	17,810	108,849	

*Formula = $S=\frac{Pr}{t}$

S=Ultimate Strength (psi)
P=Burst Pressure
r=Radius to I. D.
t=Wall Thickness @ minimum value

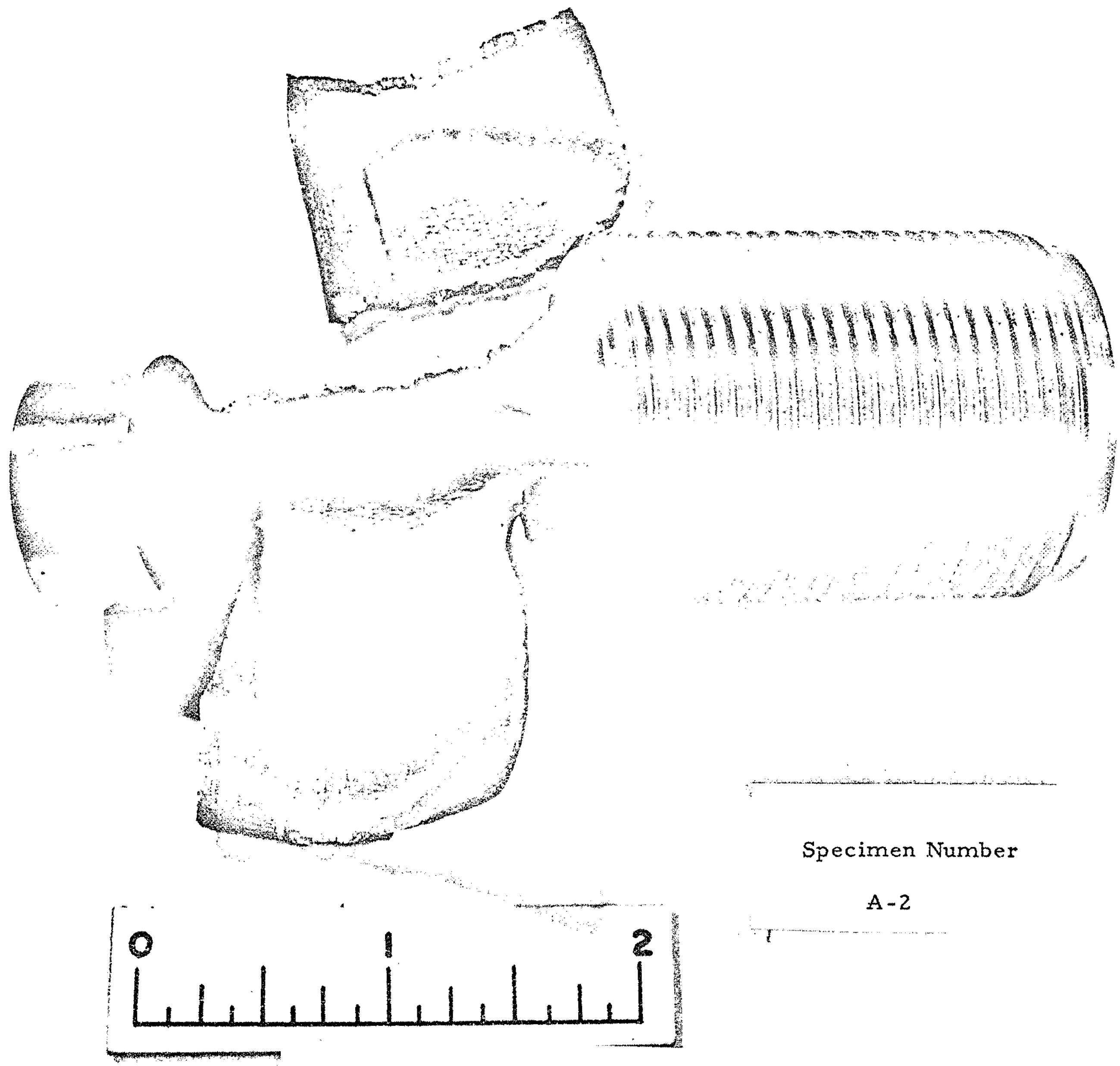


Figure 3-2. Typical Burst Specimen

SECTION IV

24 HOUR HELIUM AND HYDROGEN STORAGE AND BURST TEST PRESSURIZED THIN WALL CYLINDERS

A. TEST REQUIREMENTS

1. The test specimens were to be installed in a test fixture as shown in Figure 2-1B. Specimens B1 through B12, and D1 through D12 were to be subjected to this test.

2. The specimens were to be pressurized for the periods and to the pressures listed in Table 4-1 below:

Table 4-1. Specimen Storage Pressure and Period

Specimens	Pressure (psig)	Test Medium	Time Period (Hours)
B1-B6	6,000 + 600-0	Helium	24 ± 2
D1-D6	6,000 + 600-0	Hydrogen	24 ± 2
B7-B12	10,000 + 1000-0	Helium	24 ± 2
D7-D12	10,000 + 1000-0	Hydrogen	24 ± 2

3. Following the pressurization periods shown above, the specimens were to be individually subjected to increasing internal pressure with GN_2 until burst.

4. The rate of pressurization and pressure at failure was to be graphically recorded.

B. TEST PROCEDURE

1. The test specimen and test fixture were installed in the pressurization system illustrated in Figure 4-1 utilizing equipment listed in Table 4-2.

2. Hand valves (3), (5) and (6) were opened and valve (4) was closed.

3. The specimens were pressurized to the pressures shown in Table 4-1.

4. The system was observed for leakage. When leakage was evidenced the specimens were de-pressurized and the cause of the leakage eliminated prior to re-pressurization.

5. In-line valves (3) and (5) were closed and valve (4) was gradually opened to release entrapped pressure.

6. The storage assembly was disconnected from the test system. The storage assembly consisted of the test specimen (9), the test fixture (8), hand valves (5) and (6), and pressure gage (7).

7. A warning tag was attached to each unit and the units were safely stored for the period of time specified in Table 4-1. The pressurization sequence was staggered to provide sufficient time between tests to allow for necessary burst test preparation. Frequent inspections were made to assure that the pressure remained within the required pressure range. Specimens in which pressure decay occurred were re-pressurized and the associated data recorded.

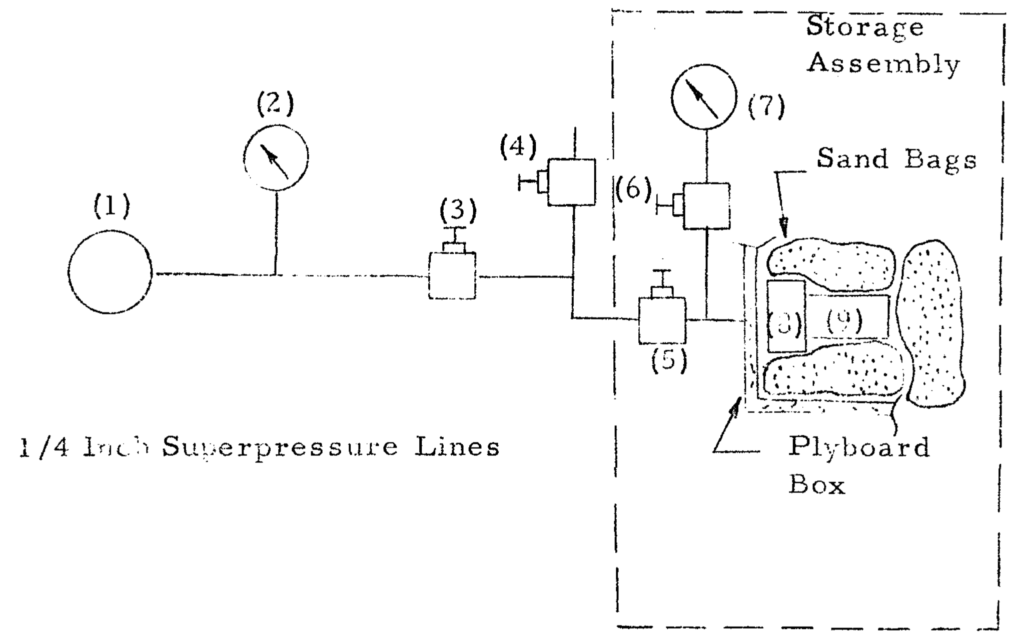


Figure 4-1. Helium and Hydrogen Pressurization Setup

8. The storage assembly was connected to the burst setup illustrated in Figure 4-2 with all valves closed. Valves (3) and (10) were opened and the pressure equalized on both sides of valve (5) by use of intensifier (1).

9. Hand valve (5) was opened and gauge isolation valve (6) was closed. Gauge (7) was removed from the system. Valve (10) was closed. Valve (3) was opened.

10. Hand valve (13) was opened and the system was pressurized with GN_2 to 22,000 psig by operation of the intensifier (1). The pressure was monitored on gage (2).

11. Hand valve (3) was closed and the recorder (16) was started.

12. The pneumatically operated valve (10) was opened by energizing the 3-way solenoid valve (14).

13. The pressure was allowed to rise until the specimen ruptured. The pneumatically operated valve (10) was closed by de-energizing the 3-way solenoid valve (14), and the recorder was stopped.

14. Steps 1 through 13 were repeated for the remaining specimens.

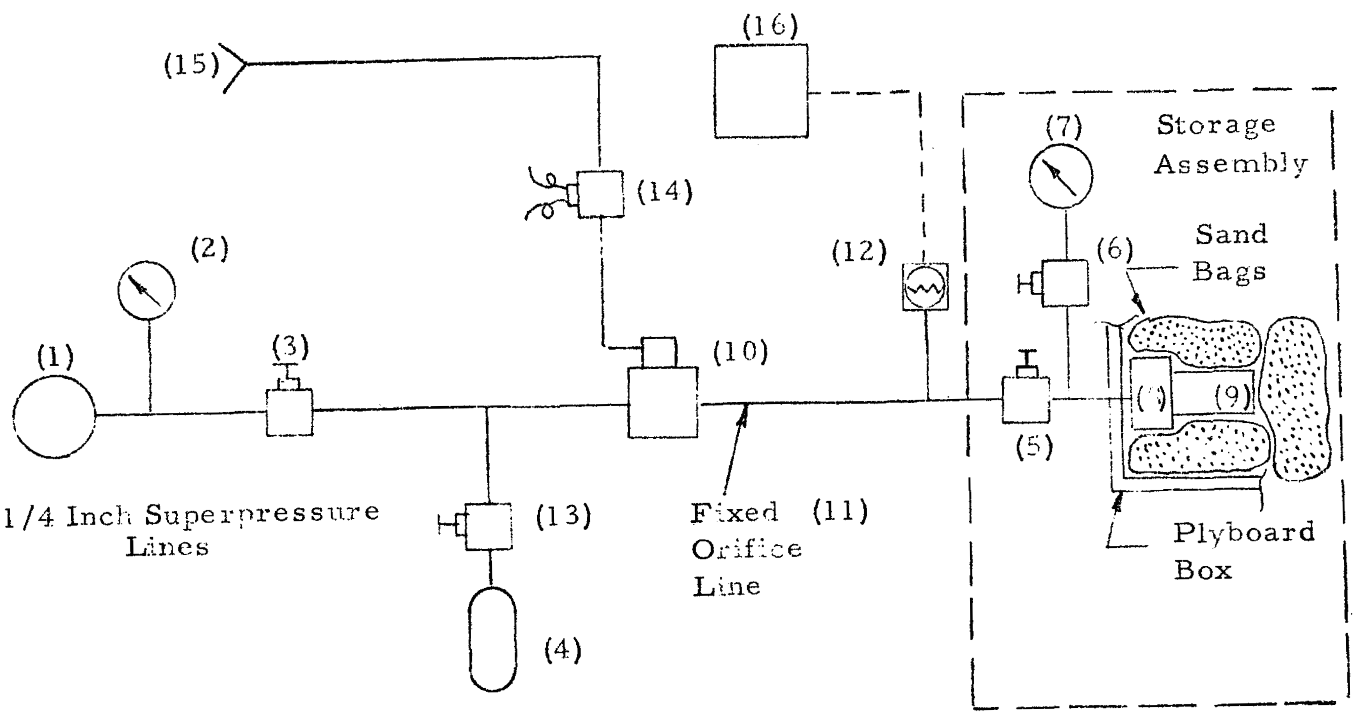


Figure 4-2. Helium and Hydrogen Burst Test Setup

Table 4-2. Helium and Hydrogen Pressurization Test Equipment List

Item No.	Item	Manufacturer	Model/ Part No.*	Serial No. *	Remarks
1.	Intensifier	American Instrument Co.	46-4021-M	EE-6668	0-30,000 psig Pneumatic
2.	Pressure Gage	Heise	N/A	N/A	30,000 psig F.S. $\pm$ 1/2% accuracy
3.	Hand Valve	Autoclave	30VM4071	N/A	0-30,000 psig
4.	Hand Valve	Autoclave	30VM4071	N/A	0-30,000 psig
5.	Hand Valve	Autoclave	30VM4071	N/A	0-30,000 psig
6.	Hand Valve	Autoclave	30VM4071	N/A	0-30,000 psig
7.	Pressure Gage	Martin-Decker & Heise	N/A	N/A	0-10,000 psig F.S. or 0-15,000 psig F.S. $\pm$ 1/2% accuracy
8.	Test Fixture	Brown	N/A	N/A	Fabricated
9.	Test Specimen	Brown	N/A	N/A	A302B Steel

Table 4-3. Helium & Hydrogen Burst Pressure Test Equipment List

Item No.	Item	Manufacturer	Model/ Part No.	Serial No.	Remarks
1.	Intensifier	American Instrument Co.	46-4021-M	EE-6668	0-30,000 psig pneumatic
2.	Pressure Gage	Heise	N/A	N/A	30,000 psig range ±1/2% Accuracy
3.	Hand Valve	Autoclave	30VM4071	N/A	1/4 inch size, 0-30,000 psig
4.	Pressure Vessel	GFE	None	N/A	50,000 psig rating
5.	Hand Valve (24 Req'd)	Autoclave	30VM4071	N/A	1/4 inch size, 30,000 psig rating
6.	Hand Valve (24 Req'd)	Autoclave	30VM4071	N/A	1/4 inch size, 30,000 psig rating
7.	Pressure Gage (24 Req'd)	Martin-Decker and Heise	N/A	N/A	0-10,000 psig or 0-15,000 psig ±1/2% F.S.
8.	Test Fixture	Brown	N/A	N/A	Fabricated
9.	Test Specimen	Brown	N/A	N/A	A302 B Steel
10.	Pneumatic operated Valve	Autoclave	30VM4971 with "OM" operator	N/A	1/4 inch size, 30,000 psig rating
11.	Fixed orifice	Brown Engr. Company, Inc.	N/A	N/A	Fabricated 60,000 psig rating
12.	Pressure Transducer	Strain-Seat	None	N/A	0-50,000 psig rating ± .5%
13.	Hand Valve	Autoclave	30VM4071	N/A	1/4 inch size, 30,000 psig rating

Table 4-3. Helium & Hydrogen Burst Pressure Test Equipment List (Continued)

Item No.	Item	Manufacturer	Model/ Part No.	Serial No.	Remarks
14.	Solenoid operated valve (3-way)	Marotta	109	MV-123B	1/4 inch size, 200 psig
15.	Air Supply	N/A	N/A	N/A	100 psig
16.	Recorder	Honeywell	1508		Oscillograph

C. TEST RESULTS

1. The ultimate stress of the specimens stored with helium at 6,000 psig ranged from 102,768 psi to 120,242 psi. The average ultimate stress was 108,469 psi.

2. The ultimate stress of the specimens stored with helium at 10,000 psig ranged from 101,344 psi to 118,186 psi. The average ultimate stress was 112,534 psi.

3. The ultimate stress of the specimens stored with hydrogen at 6,000 psig ranged from 95,678 psi to 113,141 psi. The average ultimate stress was 100,446 psi.

4. The ultimate stress of the specimens stored with helium at 10,000 psig ranged from 95,534 psi to 124,494 psi. The average ultimate stress was 106,070.

D. TEST DATA

The test data are presented in Tables 4-4, 4-5, 4-6 and 4-7.

Table 4-4. Burst Pressure Data-6000 PSIG He Storage for 24 Hours

Specimen	Burst Pressure (psig)	Ultimate Stress (psi)	Minimum Wall Thickness (Inch)	Outside Diameter (Inch)
B-1	17,515	105,830	0.0710	1.0000
B-2	16,900	103,666	0.0701	1.0002
B-3	17,545	107,610	0.0701	1.0001
B-4	19,800	120,242	0.0707	1.0001
B-5	17,120	102,768	0.0707	1.0002
B-6	18,170	110,682	0.0705	0.9999
Average	17,841	108,469	0.0705	1.0001

Table 4-5. Burst Pressure Data-10,000 PSIG He Storage for 24 Hours

Specimen	Burst Pressure (psig)	Ultimate Stress (psi)	Minimum Wall Thickness (Inch)	Outside Diameter (Inch)
B-7	19,363	118,186	0.0704	1.0002
B-8	17,865	108,837	0.0705	1.0000
B-9	18,800	114,886	0.0703	0.9998
B-10	18,770	113,961	0.0707	0.9999
B-11	19,400	117,994	0.0706	1.0000
B-12	16,690	101,344	0.0707	1.0000
Average	18,481	112,534	0.0705	1.0000

Table 4-6. Burst Pressure Data-6000 PSIG H_2 Storage for 24 Hours

Specimen	Burst Pressure (psig)	Ultimate Stress (psi)	Minimum Wall Thickness (Inch)	Outside Diameter (Inch)
D-1	18,725	113,141	0.0710	1.000
D-2	16,460	100,278	0.0705	1.000
D-3	16,000	96,676	0.0710	1.000
D-4	16,485	100,430	0.0705	1.000
D-5	15,705	96,474	0.0700	1.000
D-6	15,705	95,678	0.0705	1.000
Average	16,513	100,446	0.0706	1.000

Table 4-7. Burst Pressure Data-10,000 PSIG H_2 Storage for 24 Hours

Specimen	Burst Pressure (psig)	Ultimate Stress (psi)	Minimum Wall Thickness (Inch)	Outside Diameter (Inch)
D-7	15,480	95,534	0.0710	1.000
D-8	17,820	109,466	0.0700	1.000
D-9	16,870	101,933	0.0710	1.000
D-10	20,435	124,494	0.0705	1.000
D-11	17,210	103,987	0.0710	1.000
D-12	16,580	101,009	0.0705	1.000
Average	17,399	106,070	0.0707	1.000

SECTION V

720 HOUR HELIUM AND HYDROGEN STORAGE AND BURST TEST PRESSURIZED THIN WALL CYLINDERS

A. TEST REQUIREMENTS

1. The test specimens were to be installed in a test fixture as shown in Figure 2-1B. Specimens C1 through C12, and E1 through E12 were to be subjected to this test.

2. The specimens were to be pressurized for the periods and to the pressures listed in Table 5-1 below:

Table 5-1. Specimen Storage Pressure and Period

Specimens	Pressure (psig)	Test Medium	Time Period (Hours)
C1 - C6	6,000 + 600-0	Helium	720 ± 2
E1 - E6	6,000 + 600-0	Hydrogen	720 ± 2
C7 - C12	10,000 + 1000-0	Helium	720 ± 2
E7 - E12	10,000 + 1000-0	Hydrogen	720 ± 2

3. Following the pressurization periods shown above, the specimens were to be individually subjected to increasing internal pressure with GN_2 until burst.

4. The rate of pressurization and pressure at failure was to be graphically recorded.

B. TEST PROCEDURE

1. The test specimen and test fixture were installed in the pressurization system illustrated in Figure 5-1 utilizing equipment listed in Table 5-2.

2. Hand valves (3), (5) and (6) were opened and valve (4) was closed.

3. The specimens were pressurized to the pressures shown in Table 5-1.

4. The system was observed for leakage. When leakage was evidenced the specimen was de-pressurized and the cause of the leakage eliminated prior to re-pressurization.

5. In-line valves (3) and (5) were closed and valve (4) was gradually opened to release entrapped pressure.

6. The storage assembly was disconnected from the test system. The storage assembly consisted of the test specimen (9), the test fixture (8), hand valves (5) and (6), and pressure gage (7)

7. A warning tag was attached to each unit and the units were safely stored for the period of time specified in Table 5-1. The pressurization sequence was staggered to provide sufficient time between tests to allow for necessary burst test preparation. Frequent inspections were made to assure that the pressure remained within the required pressure range. Specimens in which pressure decay occurred were re-pressurized and the associated data recorded.

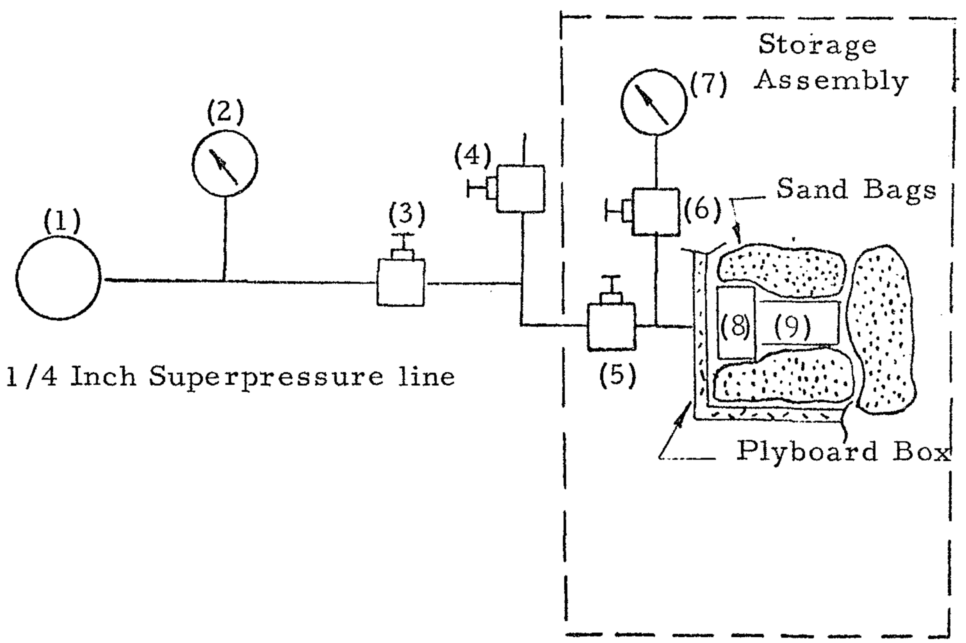


Figure 5-1. Helium and Hydrogen Pressurization Setup

8. The storage assembly was connected to the burst setup illustrated in Figure 5-2 with all valves closed. Valves (3) and (10) were opened and the pressure equalized or both sides of valve (5) by use of intensifier (1).

9. Hand valve (5) was opened and gage isolation valve (6) was closed. Gage (7) was removed from the system. Valve (10) was closed.

10. Hand valves (3) and (13) were opened and the system was pressurized with GN_2 to 22,000 psig by operation of the intensifier (1); the pressure was monitored on gage (2).

11. Hand valve (3) was closed and the recorder (16) was started.

12. The pneumatically operated valve (10) was opened by energizing the 3-way solenoid valve (14).

13. The pressure was allowed to rise until the specimen ruptured. The pneumatically operated valve (10) was closed by de-energizing the 3-way solenoid valve (14), and the recorder was stopped.

14. Steps 1 through 13 were repeated for the remaining specimens.

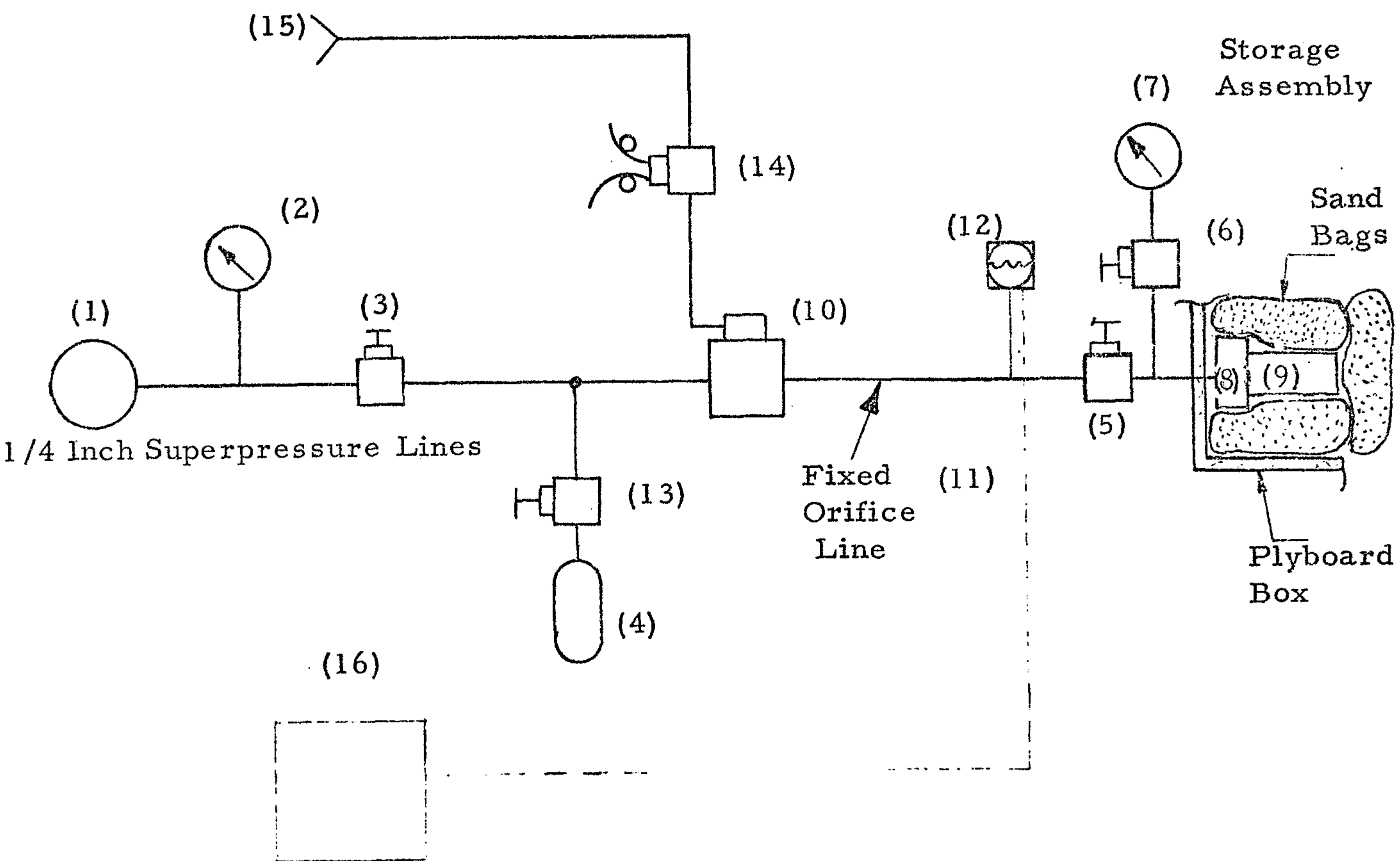


Figure 5-2. Helium and Hydrogen Burst Test Setup.

Table 5-2. Helium & Hydrogen Pressurization Test Equipment List

Item No.	Item	Manufacturer	Model/ Part No.	Serial No.	Remarks
1	Intensifier	American Instrument Co.	46-4021-M	EE-6668	0-30,000 psig pneumatic
2	Pressure Gage	Heise	N/A	N/A	30,000 psig F.S. $\pm 1/2\%$ accuracy
3	Hand Valve	Autoclave	30VM40 71	N/A	0-30,000 psig 1/4 inch size
4	Hand Valve	Autoclave	30VM40 71	N/A	0-30,000 psig 1/4 inch size
5	Hand Valve	Autoclave	30VM40 71	N/A	0-30,000 psig 1/4 inch size
6	Hand Valve	Autoclave	30VM40 71	N/A	0-30,000 psig 1/4 inch size
7	Pressure Gage	Martin-Decker & Heise	N/A	N/A	0-10,000 psig F.S, or 0-15,000 psig F.S., $\pm 1/2\%$ accuracy
8	Test Fixture	Brown	N/A	N/A	Fabricated
9	Test Specimen	Brown	N/A	N/A	A 302B Steel

Table 5-3. Helium and Hydrogen Burst Pressure Test Equipment List

Item No.	Item	Manufacturer	Model/ Part No.	Serial No.	Remarks
1	Intensifier	American Instrument Co.	46-4021-M	EE-6668	0-30,000 psig pneumatic
2	Pressure Gage	Heise and Autoclave	N/A	N/A	30,000 psig range ±1/2% accuracy
3	Hand Valve	Autoclave	30VM4071	N/A	0-30,000 psig
4	Pressure Vessel	GFE	N/A	N/A	50,000 psig rating
5	Hand Valve (24 Req'd)	Autoclave	30VM4071	N/A	30,000 psig rating 1/4 inch size
6	Hand Valve (24 Req'd)	Autoclave	30VM4071	N/A	30,000 psig rating 1/4 inch size
7	Pressure Gage (24 Req'd)	Martin-Decker and Heise	N/A	N/A	0-10,000 psig or 0-15,000 psig ± 1/2% F.S. acc.
8	Test Fixture (24 Req'd)	Brown	N/A	N/A	Fabricated
9	Test Specimen	Brown	N/A	N/A	A302 B Steel
10	Pneumatic Operated Valve	Autoclave	30VM4071 with "OM" operator	N/A	1/4 inch size 30,000 psig rating
11	Fixed Orifice	Brown Engr. Company, Inc.	None	None	Fabricated 60,000 psig rating
12	Pressure Transducer	B. L. H.	GPCG	33553	0-20,000 psig rating ±.5%
13	Hand Valve	Autoclave	30VM4071	N/A	30,000 psig rating

Table 5-3. Helium and Hydrogen Burst Pressure Test Equipment List (Cont'd)

Item No.	Item	Manufacturer	Model/ Part No.	Serial No.	Remarks
14	Solenoid Operated Valve (3-way)	Marotta	109	MV-123B	200 psig
15	Air Supply	N/A	N/A	N/A	100 psig
16	Recorder	Honeywell	1508		

C. TEST RESULTS

1. The ultimate stress of the specimens stored with helium at 6000 psig ranged from 117,011 psi to 124,158 psi. The average ultimate stress was 120,609 psi.

2. The ultimate stress of the specimens stored with helium at 10,000 psig ranged from 114,533 psi to 125,343 psi. The average ultimate stress was 120,532 psi.

3. The ultimate stress of the specimens stored with hydrogen at 6,000 psig ranged from 111,526 psi to 124,880 psi. The average ultimate stress was 116,944 psi.

4. The ultimate stress of the specimens stored with hydrogen at 10,000 psig ranged from 104,277 psi to 122,453 psi. The average ultimate stress was 118,277 psi.

D. TEST DATA

The test data are presented in Tables 5-4, 5-5, 5-6 and 5-7.

Table 5-4. Burst Pressure Data - 6000 psig He Storage for 720 Hours

Specimen	Burst Pressure (psig)	Ultimate Stress (psi)	Minimum Wall Thickness (Inch)	Outside Diameter (Inch)
C-1	20,100	121,520	.071	1.0005
C-2	19,200	117,011	.0705	1.0003
C-3	19,300	118,698	.070	1.0005
C-4	20,200	124,158	.070	1.0005
C-5	19,600	118,525	.071	1.0007
C-6	20,300	123,744	.0705	1.0005
Average	19,783	120,609	.0705	1.0005

Table 5-5. Burst Pressure Data-10,000 psig He Storage for 720 Hours

Specimen	Burst Pressure (psig)	Ultimate Stress (psi)	Minimum Wall Thickness (Inch)	Outside Diameter (Inch)
C-7	19,400	119,171	.070	1.0000
C-8	20,100	120,915	.071	1.0005
C-9	18,800	114,533	.0705	1.0000
C-10	19,800	121,328	.0705	1.0050
C-11	20,000	121,901	.0705	1.0004
C-12	20,400	125,343	.070	1.0002
Average	19,750	120,532	.0704	1.0010

Table 5-6. Burst Pressure Data-6,000 psig H_2 Storage for 720 Hours

Specimen	Burst Pressure (psig)	Ultimate Stress (psi)	Minimum Wall Thickness (Inch)	Outside Diameter (Inch)
E-1	18,600	113,168	.0706	1.0003
E-2	20,600	124,880	.0708	1.0000
E-3	17,900	108,987	.0705	0.9995
E-4	19,300	117,800	.0705	1.0003
E-5	19,600	120,043	.0702	1.0003
E-6	20,200	123,062	.0705	1.0000
Average	19,367	117,990	.0705	1.0001

Table 5-7. Burst Pressure Data-10,000 psig H_2 Storage for 720 Hours

Specimen	Burst Pressure (psig)	Ultimate Stress (psi)	Minimum Wall Thickness (Inch)	Outside Diameter (Inch)
E-7	20,100	122,308	.0706	1.0004
E-8	20,100	122,453	.0705	1.0000
E-9	20,100	122,050	.0707	1.0000
E-10	19,300	117,648	.0705	1.0005
E-11	19,700	120,414	.0703	1.0000
E-12	17,200	104,786	.0705	1.0000
Average	19,417	118,277	.0705	1.0002

SECTION VI

INSPECTION, CLEANING AND ASSEMBLY

PRESSURIZED TENSILE SPECIMENS

A. TEST REQUIREMENTS

The specimens and test fixtures were to be dimensionally inspected for conformance to design requirements. Each specimen was to be identified for future reference. The actual diameter of each specimen was to be measured and recorded within $\pm$ 0.001 inch, at the minimum value.

The test fixtures, associated system and specimens were to be cleaned to eliminate hydrocarbons and oxides and maintained in an oxygen free atmosphere.

The specimens were to be installed in the test fixtures as shown in Figure 6-1. A light coating of KEL-F-90 lubricant was to be applied on the "O" ring seals while maintaining an inert atmosphere.

After each test setup was complete, and before "storing" the helium specimens, all system piping downstream of the intensifier was to be pressurized to 6000 psig and the piping checked for leaks. A helium leak detector was to be used.

Prior to the storage of any hydrogen, all system piping downstream of the purifier was to be evacuated to 10^{-3} microns and maintained at this condition for at least 24 hours after all detectable leaks had been sealed. A helium leak detector was to be used.

B. TEST PROCEDURE

1. After machining of the specimens and fixtures, a dimensional inspection was performed to insure conformance to Figure 1-2. All applicable data was recorded.

2. Each specimen was marked on the upper end (see Figure 1-2) using the designations given in Table 1-2. Caution was exercised to prevent damaging surfaces.

3. The test fixtures and specimens were cleaned with trichloroethylene and ultrasonic cleaner. Each fixture and the associated system

was purged with ultra-pure helium gas to maintain an oxygen free atmosphere.

4. Specimens X-2F through X-2J were assembled in an oxygen free environment as follows:

a. Lubricated "O" rings and back-up rings were installed at "A" and "B" as shown in Figure 6-1.

b. The plunger was inserted into fixture in the direction of arrow "D" until "O" ring groove "C" was visible at opposite end.

c. The lubricated "O" ring and back-up ring was installed at "C" and the plunger installed in the final position.

d. The plate was attached to fixture and plunger with screws and the inlet and outlet valves installed.

5. After assembly, the specimens were pressurized with ultra-pure helium gas, to approximately 100 psig.

6. All openings to the assembly were covered with two (2) layers of aluminum foil and two (2) layers of polethylene held in place with white vinyl tape.

7. Specimens X-2F through X-2J were connected with the associated pressure storage equipment shown in Figure 7-1 and listed in Table 7-1.

8. Upon completion of each phase of burst testing, the remaining portion of the test specimen was removed from the fixture.

9. Steps three (3) through seven (7) were repeated with the remaining specimens as the test fixtures and associated equipment became available.

C. TEST RESULTS

All specimens were within tolerance.

D. TEST DATA

The inspection data are presented in Table 6-1.

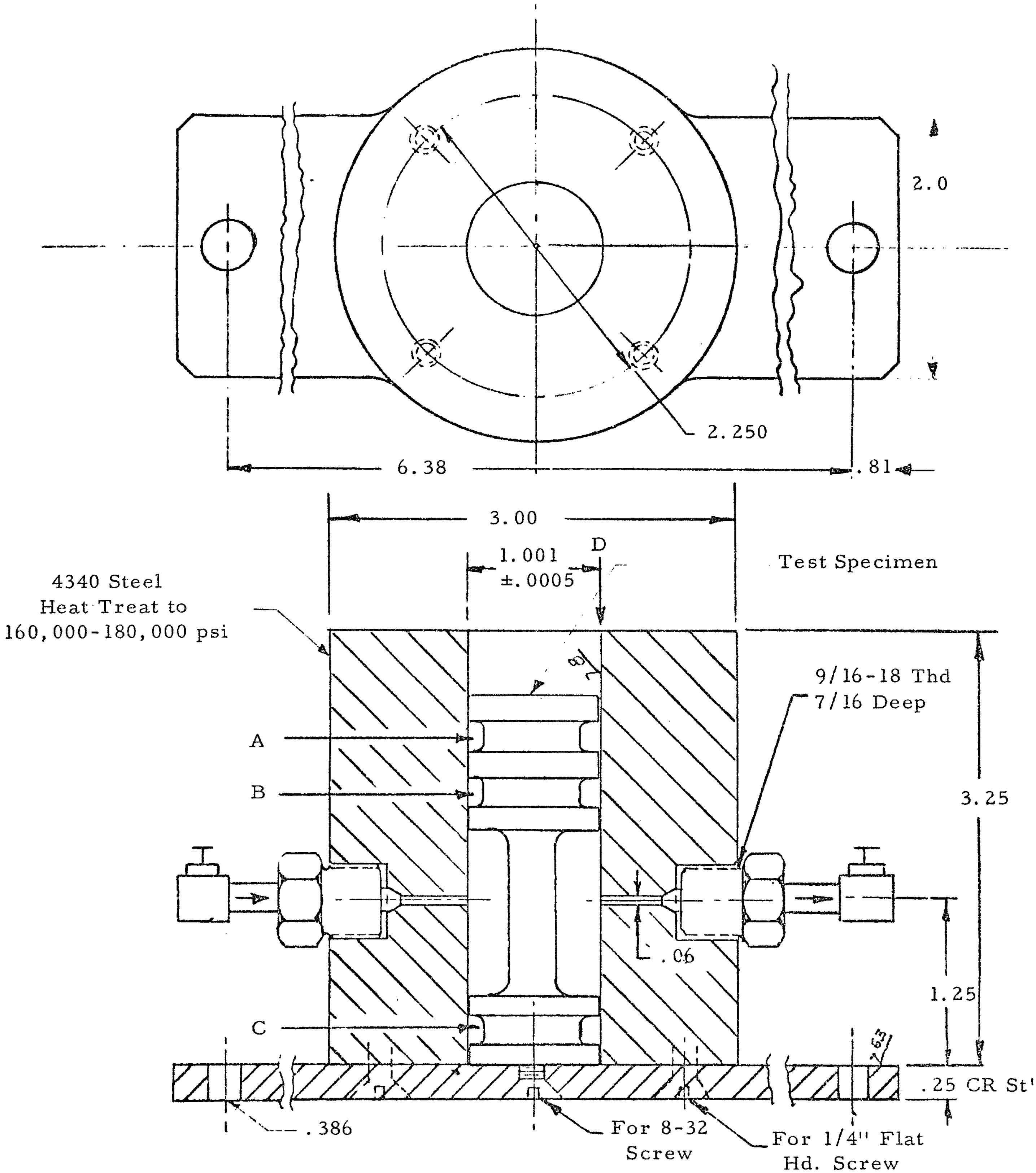
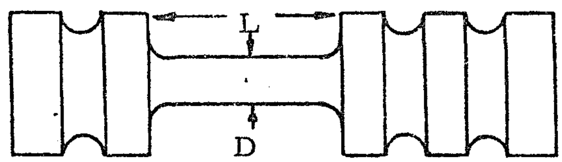


Figure 6-1. Specimen Installed in Test Fixture

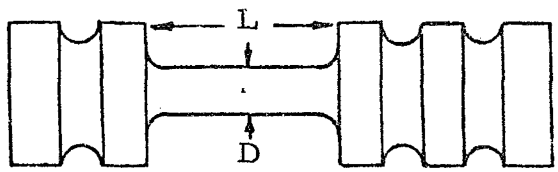
Table 6-1. Inspection Data



All Dimensions Are Shown In Inches.

Specimen	Dimension L		Dimension D (Minimum)	
	Specified	Actual	Specified	Actual
X-1A	1.25	1.261	.370	.370
X-1B	1.25	1.240	.370	.3699
X-1C	1.25	1.257	.370	.370
X-1G	1.25	1.258	.370	.3792
X-1H	1.25	1.260	.370	.3796
X-2A	1.25	1.245	.329	.329
X-2B	1.25	1.245	.329	.329
X-2C	1.25	1.245	.329	.329
X-2D	1.25	1.245	.329	.3292
X-2E	1.25	1.246	.329	.3288
X-2F	1.25	1.248	.329	.3289
X-2G	1.25	1.245	.329	.3292
X-2H	1.25	1.245	.329	.329
X-2I	1.25	1.245	.329	.329
X-2J	1.25	1.244	.329	.329
X-2K	1.25	1.250	.329	.3292
X-3A	1.25	1.245	.280	.2798

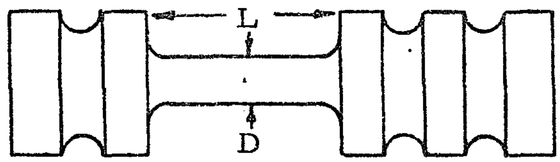
Table 6-1. Inspection Data (Continued)



All Dimensions Are Shown In Inches.

Specimen	Dimension L		Dimension D (Minimum)	
	Specified	Actual	Specified	Actual
X-3B	1.25	1.241	.280	.2798
X-3C	1.25	1.245	.280	.2799
X-3D	1.25	1.250	.280	.2795
X-3E	1.25	1.242	.280	.2795
X-3F	1.25	1.245	.280	.2797
X-3G	1.25	1.244	.280	.2796
X-3H	1.25	1.243	.280	.2782
X-3I	1.25	1.250	.280	.280
X-3J	1.25	1.244	.280	.2795
X-3K	1.25	1.251	.280	.2799
X-3L	1.25	1.247	.280	.2798
X-3M	1.25	1.245	.280	.2796
X-3N	1.25	1.245	.280	.2798
X-30	1.25	1.245	.280	.280
X-3P	1.25	1.247	.280	.280
X-4A	1.25	1.245	.245	.2446
X-4B	1.25	1.238	.245	.2448

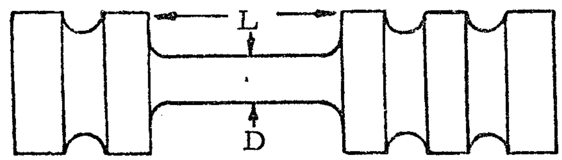
Table 6-1. Inspection Data (Continued)



All Dimensions Are Shown In Inches.

Specimen	Dimension L		Dimension D (Minimum)	
	Specified	Actual	Specified	Actual
X-4C	1.25	1.240	.245	.2448
X-4D	1.25	1.241	.245	.2444
X-4E	1.25	1.244	.245	.2447
X-4F	1.25	1.240	.245	.2446
X-4G	1.25	1.242	.245	.2445
X-4H	1.25	1.255	.245	.2447
X-4I	1.25	1.242	.245	.2446
X-4J	1.25	1.240	.245	.2447
X-4K	1.25	1.245	.245	.2448
X-5A	1.25	1.245	.238	.2358
X-5B	1.25	1.246	.238	.2355
X-5C	1.25	1.241	.238	.2359
X-5D	1.25	1.240	.238	.2356
X-5E	1.25	1.240	.238	.2358
X-5F	1.25	1.241	.238	.2356
X-5G	1.25	1.242	.238	.2355
X-5H	1.25	1.241	.238	.2348

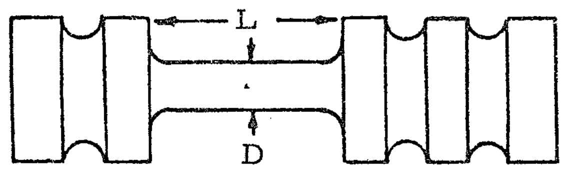
Table 6-1. Inspection Data (Continued)



All Dimensions Are Shown In Inches.

Specimen	Dimension L		Dimension D (Minimum)	
	Specified	Actual	Specified	Actual
X-5I	1.25	1.240	.238	.2357
X-5J	1.25	1.240	.238	.2356
X-5K	1.25	1.248	.238	.2378
X-6A	1.25	1.250	.227	.227
X-6B	1.25	1.249	.227	.2268
X-6C	1.25	1.250	.227	.2269
X-6D	1.25	1.247	.227	.2269
X-6E	1.25	1.250	.227	.2269
X-6F	1.25	1.247	.227	.2269
X-6G	1.25	1.248	.227	.2268
X-6H	1.25	1.245	.227	.2267
X-6I	1.25	1.244	.227	.2268
X-6J	1.25	1.247	.227	.2268
X-6K	1.25	1.253	.227	.2268
X-6L	1.25	1.246	.227	.2271
X-6M	1.25	1.243	.227	.2272
X-6N	1.25	1.245	.227	.2271

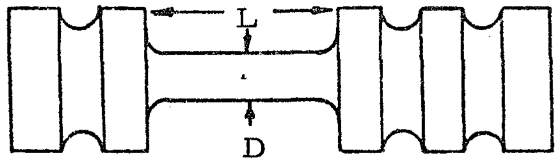
Table 6-1. Inspection Data (Continued



All Dimensions Are Shown In Inches.

Specimen	Dimension L		Dimension D (Minimum)	
	Specified	Actual	Specified	Actual
X-6O	1.25	1.260	.227	.227
X-6P	1.25	1.245	.227	.227
X-7A	1.25	1.244	.218	.2177
X-7B	1.25	1.243	.218	.2178
X-7C	1.25	1.248	.218	.2178
X-7D	1.25	1.250	.218	.218
X-7E	1.25	1.242	.218	.2177
X-7F	1.25	1.245	.218	.2178
X-7G	1.25	1.242	.218	.2172
X-7H	1.25	1.245	.218	.2178
X-7I	1.25	1.242	.218	.2174
X-7J	1.25	1.240	.218	.2181
X-7K	1.25	1.268	.218	.2180
X-8B	1.25	1.241	.211	.2107
X-8C	1.25	1.241	.211	.2105
X-8D	1.25	1.240	.211	.2108
X-8E	1.25	1.240	.211	.211

Table 6-1. Inspection Data (Continued)



All Dimensions Are Shown In Inches.

Specimen	Dimension L		Dimension D (Minimum)	
	Specified	Actual	Specified	Actual
X-8F	1.25	1.241	.211	.2108
X-8G	1.25	1.243	.211	.2108
X-8H	1.25	1.245	.211	.2103
X-8I	1.25	1.241	.211	.2106
X-8J	1.25	1.242	.211	.2107
X-8K	1.25	1.241	.211	.2109

SECTION VII

STORAGE PRESSURE AND BURST TEST

PRESSURIZED TENSILE SPECIMENS

A. TEST REQUIREMENTS

The specimens were to be subjected, in groups of five (5), to a stess level between 50,000 and 130,000 psi for a period of twenty-four hours (unless failure occurred before then). After twenty-four (24) hours, the specimen stress was to be increased until failure occurred.

Calibration pressure runs were to be performed on dummy specimens as required to insure accuracy of instrumentation and to establish a satisfactory pressure rise rate.

An energy dissipation unit design was to be evaluated in this test phase for use in the following phases for personnel protection.

The specimens were to be pressurized at a constant rate, utilizing gaseous hydrogen or helium as the test medium.

The test report was to include: some typical tapes (illustrations), and plots of storage stress and storage time vs. % elongation, % reduction (necking) and ultimate tensile strength. The helium and hydrogen tests were to be plotted on the same graph for comparison.

B. TEST PROCEDURE

1. The pressurization system downstream of the purifier, as shown in Figure 7-1, was cleaned by sonic cleaning using trichloroethylene and GN_2 drying.

2. The specimens were tested in the sequence listed in Table 7-1. The media used with each specimen is listed in Table 7-1.

3. The specimens were installed in the pressurization system illustrated in Figure 7-1. All valves were closed. The equipment used is listed in Table 7-2. The safety setup for personnel protection is shown in Figure 7-2.

NOTE:

The system was pressurized and leak checked using a helium leak detector. All leaks were stopped. The system was evacuated and all fittings were painted with Glyptol.

4. All specimens exposed to helium or nitrogen were tested as follows:

a. A GHe or GN_2 (14a) and (14b) supply was connected to valve (4b).

b. Valves (8a), (5), (4b), (2g), (2k), (2m), (2n), (2r), (2q), (2s), (2v), (2y), (2ab), (2ae), (2u), (2x), (2aa), (2ad), and (2ag) were opened.

NOTE:

When GHe or GN_2 supply was exhausted, valves (8a) and (5) were closed and valve (8b) opened.

c. Valve (2t) was cracked and GHe or GN_2 bled for approximately 30 seconds.

d. Valves (2t) and (2u) were closed.

e. Steps 4c was repeated with valve (2w).

f. Valves (2w) and (2x) were closed.

g. Steps 4c was repeated with valve (2z).

h. Valves (2z) and (2aa) were closed.

i. Step 4c was repeated with valve (2ac).

j. Valves (2ac) and (2ad) were closed.

k. Step 4c was repeated with valve (2af).

l. Valves (2af) and (2ag) were closed.

m. Valves (2v), (2y), (2ab) and (2ae) were closed.

n. Intensifier (1) was started and pressure transducer (12e) calibrated with pressure gage (18).

o. Valve (2t) was closed and valve (2v) then opened.

p. Step 4n was repeated with pressure transducer (12d).

q. Valve (2v) was closed and valve (2y) then opened.

r. Step 4n was repeated with pressure transducer (12c).

s. Valve (2y) was closed and valve (2ab) then opened.

t. Step 4n was repeated with pressure transducer (12b).

u. Valve (2ab) was closed and valve (2ae) then opened.

v. Step 4n was repeated with pressure transducer (12a).

w. Valves (2s), (2t), (2v), (2w), (2y), (2z), (2ab), (2ac) and (2af) were opened.

x. Intensifier (1) was started and the specimens pressurized to 6000 (+200, -0) psig as indicated by pressure gage (18).

y. The intensifier (1) was stopped and valves (2s), (2v), (2y), (2ab) and (2ae) closed.

z. The specimen pressure, as indicated by pressure transducers, was monitored for 24 hours. If this pressure dropped below 6000 psig, the specimen was pressurized to 6000 (+200, -0) psig and the associated data recorded.

aa. At the conclusion of the 24 hour storage period, intensifier (1) was started and the system pressure increased to 6000 psig as indicated by pressure gage (18). Intensifier (1) was then stopped.

ab. Valve (2ae) was opened and valve (2q) closed.

ac. Intensifier (1) was started and pressure increased until specimen failure. Pressure, as indicated by pressure transducer (12a), was recorded during the burst operation.

ad. Valve (2ae) was closed.

ae. Valve (2q) was opened and step 4aa repeated. Valve (2q) was then closed.

af. Valve (2ab) was opened and step 4ac repeated.

ag. Valve (2ab) was closed.

ah. Step 4ae was repeated.

ai. Valve (2y) was opened and step 4aa repeated.

aj. Valve (2y) was closed.

ak. Step 4ae was repeated.

al. Valve (2v) was opened and step 4ac repeated.

am. Valve (2v) was closed.

an. Step 4ae was repeated.

ao. Valve (2s) was opened and step 4ac repeated.

ap. Valve (2s) was closed.

5. All specimens exposed to hydrogen were tested as follows:

a. A GH_2 supply (15a) and (15b) was connected to filter (13).

b. Regulator (10) was closed and valves (8a), (5), and (3b) were opened.

c. Regulator (10) was adjusted to obtain a pressure of 150 psig as indicated by purifier (21) input gage.

d. The purifier (21) was set up and adjusted to obtain optimum flow.

e. Valves (4b), (9), (7) and (4e) were opened and the purifier output analyzed until the oxygen content was below 100 ppb.

f. Valve (4b) was closed.

g. Valves (2a) and (2b) were opened and the residual gas in the ullage bottles (24a) and (24b) analyzed.

h. Valves (2a), (2b), (7) and (9) were closed after it was determined the ullage GH_2 was pure.

i. Valves (4b), (4c), (2e), (2f), (2j), (2m), (2n), (21) and (6) were opened.

j. Intensifier (22) was actuated and the output analyzed until the oxygen content was less than 100 ppb. The intensifier was then stopped.

k. Valves (4c), (2e), (2f), (2j) and (2m) were closed and valves (2g) and (2k) opened.

l. Intensifier (1) was actuated and the output analyzed until the oxygen content was less than 100 ppb. The intensifier was then stopped.

m. Valve (2k), (21) and (6) were closed.

n. Valves (2h), (2j), (2n), (2s), (2t), (2u), (2v), (2w), (2x), (2y), (2z), (2aa), (2ab), (2ac), (2ad), (2ae), (2af), (2ag), (3c) and (4d) were opened and GH_2 allowed to flow through the specimens to atmosphere for 30 seconds. Valve (4d) was then closed.

o. The GH2 was analyzed through the specimens until the oxygen content was less than 100 ppb.

NOTE:

This completed the system purge. The purging gas from all parts contained less than 100 ppb of oxygen.

p. Valves (4e), (3c), (2ag), (2ad), (2aa), (2x), (2w), (2af), (2ac), (2z), (2w), (2t), (2s), (2v), (2y), (2ab), (2ae), (2j) and (2h) were closed.

q. Valves (4c), (2e), (2d), (2a), (2f), (2j), (2n), (2r) and (2q) were opened.

r. Ullage bottles (24a) and (24b) were submerged in LN_2. Intensifier (22) was energized and the ullage bottles pressurized to approximately 500 psig.

s. Intensifier (22) was stopped and valves (4b), (4c), (2e), (2f), (2d) and (2j) closed.

t. The LN_2 around the ullage bottles was drained and replaced with hot water.

u. Valves (2b), (2g), (2k), (2m) and (2s) were opened.

v. Intensifier (1) was started and pressure transducer (12e) calibrated with pressure gage (18).

w. Valves (2s) was closed and valve (2v) opened.

x. Step 5v was repeated for pressure transducer (12d).

y. Valve (2v) was closed and valve (2y) opened.

z. Steps 5v was repeated for pressure transducer (12c).

aa. Valve (2y) was closed and valve (2ab) opened.

ab. Step 5v was repeated for pressure transducer (12b).

ac. Valve (2ab) was closed and valve (2ae) opened.

ad. Step 5v was repeated for pressure transducer (12a).

ae. Valves (2s), (2t), (2v), (2w), (2y), (2z), (2ab), (2ac) and (2af) were opened.

af. Intensifier (1) was started and the specimens pressurized to 6000 (+200, -0) psig as indicated on pressure gage (18). The intensifier was then stopped.

ag. Valves (2s), (2v), (2y), (2ab) and (2ae) were closed.

ah. The specimen pressure, as indicated by pressure transducer, was monitored for 24 hours. If this pressure dropped below 6000 psig, the specimen was repressurized to 6000 (+200, -0) and the associated data recorded.

ai. Step 4aa through 4ap were repeated.

6. The specimens tested with MIL-H-5606 hydraulic fluid were installed in the test setup shown in Figure 7-3, with the equipment listed in Table 7-3. These specimens were tested as follows:

a. Valves (3) and (5) were opened and the system bled of air using a low hydraulic pressure.

b. Valve (5) was closed.

c. Hand pump (1) was actuated and the system pressure raised to 6000 (+200, -0) psig as indicated on pressure transducer (2).

d. This pressure was maintained for one hour.

e. Hand pump (1) was actuated and the hydraulic pressure increased until specimen failure. The pressure was monitored with pressure transducer (2).

C. TEST RESULTS

1. The ultimate stress of the specimens tested with GH_2 ranged from 115, 604 psi to 140, 651 psi. The ultimate stress of the specimens tested with GHe ranged from 117, 332 psi to 144, 726. The ultimate stress of the specimens tested with GN_2 ranged from 123, 588 psi to 138, 584 psi. The ultimate stress of the specimens tested with hydraulic oil (MIL-H-5606) ranged from 122, 018 to 125, 324. There was no definite effect from hydrogen embrittlement noted on the ultimate stress. The specimens stored at the higher stress generally had a higher ultimate strength. This may be attributed to strain hardening. A plot of average ultimate stress vs storage stress for GH_2 and GHe specimens is presented in Figure 7-4.

2. The area reduction of specimens tested with GH_2 ranged from 17. 5% to 65. 6%. The area reduction of specimens tested with GHe ranged from 59. 2% to 68. 5%. The area reduction of specimens tested with hydraulic oil (MIL-H-5606) ranged from 62. 5% to 66. 6%. The area reduction of specimens tested with GN_2 ranged from 61. 6% to 65. 2%. There was a definite effect on area reduction on specimens subjected to a hydrogen atmosphere. The percent of area reduction was considerably lower and much more erratic on specimens tested with hydrogen. A plot of average reduction in area vs storage stress for GH_2 and GHe specimens is presented in Figure 7-5.

3. The elongation for specimens tested with GH_2 ranged from 7. 6% to 20. 1%. The elongation for specimens tested with GHe ranged from 13. 8% to 20. 5%. The elongation for specimens tested with hydraulic oil (MIL-H-5606) ranged from 14. 0% to 17. 1%. The elongation for specimens tested with GN_2 ranged from 15. 6% to 17. 5%. There was a definite

effect on specimen elongation where specimens were subjected to a high pressure hydrogen atmosphere. The specimen elongation was lower for specimens tested with hydrogen except at 120, 000 psi storage stress. There was a larger percent elongation in specimens stored at lower stresses. This was probably caused by strain hardening at higher storage stresses. A plot of average elongation vs storage stress for GH_2 and GHe is presented in Figure 7-6.

4. Temperature may have some effect on hydrogen embrittlement. Specimens tested at temperatures lower than 32°F seem more effected by hydrogen embrittlement. Figure 7-7 illustrates the decrease in elongation and area reduction percentage as lower temperatures were encountered.

5. Storage stress seemed to have no effect on secondary cracking. Three specimens were stored at 120, 000 psi stress with hydrogen but not burst. These specimens along with burst specimens were subjected to a metallographic examination. (Report is in Appendix B.) The specimens that were not burst showed no evidence of hydrogen embrittlement.

6. The true fracture strength at the necked down area ranged from 155, 743 to 379, 901 psi for specimens tested with hydrogen. The true fracture strength for specimens tested with helium ranged from 292, 891 psi to 410, 298 psi (see Tables 7-20 and 7-21).

D. TEST DATA

The test data are presented in Tables 7-4 through 7-22.

Table 7-1. Pressurized Tensile Specimen Test Sequence

Test Specimen	Storage Stress Level (KSI)	Media	Material	High Purity Cleaning	Specimen Diameter (inches)	Test Sequence
X-2F	50	GHe	A302B	Yes	0.329	1
X-2G	50				0.329	1
X-2H	50				0.329	1
X-2I	50				0.329	1
X-2J	50	GHe			0.329	1
X-2A	50	GH_2			0.329	2
X-3A	75				0.280	2
X-4A	90				0.245	2
X-5A	100				0.238	2
X-6A	110				0.227	2
X-3C	75				0.280	3
X-3B	75				0.280	4
X-3D	75				0.280	4
X-3E	75				0.280	4
X-3K	75				0.280	4
X-5B	100				0.238	5
X-5C	100				0.238	5
X-5D	100				0.238	5
X-5E	100				0.238	5
X-5K	100	GH_2	A302B	Yes	0.238	5

Table 7-1. Pressurized Tensile Specimen Test Sequence (Continued)

Test Specimen	Storage Stress Level (KSI)	Media	Material	High Purity Cleaning	Specimen Diameter (inches)	Test Sequence
X-2B	50	GH_2	A302B	Yes	0.329	6
X-2C	50				0.329	6
X-2D	50				0.329	6
X-2E	50				0.329	6
X-2K	50				0.329	6
X-4B	90				0.245	7
X-4C	90				0.245	7
X-4D	90				0.245	7
X-4E	90				0.245	7
X-4K	90	GH_2			0.245	7
X-5F	100	GHe			0.238	8
X-5G	100				0.238	8
X-5H	100				0.238	8
X-5I	100				0.238	8
X-5J	100				0.238	8
X-4F	90				0.245	9
X-4G	90				0.245	9
X-4H	90				0.245	9
X-4I	90				0.245	9
X-4J	90	GHe	A302B	Yes	0.245	9

Table 7-1. Pressurized Tensile Specimen Test Sequence (Continued)

Test Specimen	Storage Stress Level (KSI)	Media	Material	High Purity Cleaning	Specimen Diameter (inches)	Test Sequence
X-6B	110	Mil-H -5606	A302B	No	0.227	10
X-6C	110				0.227	10
X-6D	110				0.227	10
X-6E	110				0.227	10
X-6K	110	Mil-H -5606			0.227	10
X-3F	75	GN_2			0.280	11
X-3G	75				0.280	11
X-3H	75				0.280	11
X-3I	75				0.280	11
X-3J	75	GN_2		No	0.280	11
X-6F	110	GHe		Yes	0.227	12
X-6G	110				0.227	12
X-6H	110				0.227	12
X-6I	110				0.227	12
X-6J	110				0.227	12
X-7F	120				0.218	13
X-7G	120				0.218	13
X-7H	120				0.218	13
X-7I	120	GHe	A-302B	Yes	0.218	13

Table 7-1. Pressurized Tensile Specimen Test Sequence

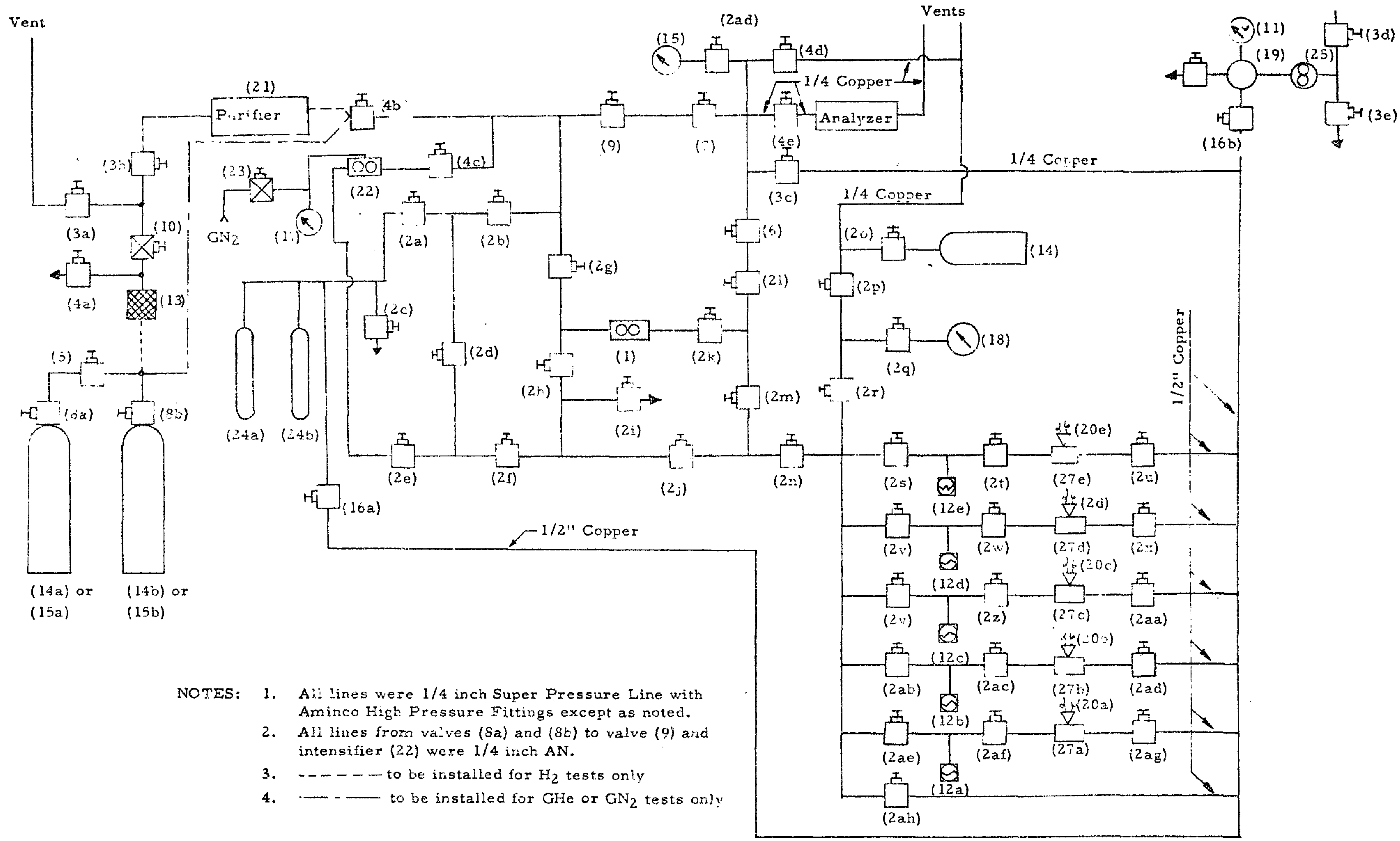
Test Specimen	Storage Stress Level (KSI)	Media	Material	High Purity Cleaning	Specimen Diameter (inches)	Test Sequence
X-7J	120	GHe	A-302B	Yes	0.218	13
X-8F*	130				0.211	14
X-8G*	130				0.211	14
X-8H*	130				0.211	14
X-8I*	130				0.211	14
X-8J*	130	GHe			0.211	14
X-2E	50	GH_2			0.329	15
X-4D	90				0.245	15
X-4E	90				0.245	15
X-4K	90				0.245	15
X-7A*	120				0.218	15
X-7B	120				0.218	16
X-7C	120				0.218	16
X-7D	120				0.218	16
X-7E	120				0.218	16
X-7K	120				0.218	16
X-6L	110				0.227	17
X-6M	110				0.227	17
X-6N	110				0.227	17
X-6O	110	GH_2	A-302B	Yes	0.227	17

*These specimens failed before or during the storage period.

Table 7-1. Pressurized Tensile Specimen Test Sequence (Continued)

Test Specimen	Storage Stress Level (KSI)	Media	Material	High Purity Cleaning	Specimen Diameter (inches)	Test Sequence
X-6P	110	GH_2	A-302B	Yes	0.227	17
X-8B*	130				0.211	18
X-8C*	130				0.211	18
X-8D*	130				0.211	18
X-8E*	130				0.211	18
X-8K*	130		A-302B		0.211	18
X-1A	37.9		4340		0.370	19
X-1B	37.9		4340		0.370	19
X-1C	37.9	GH_2	4340		0.370	19
X-3L	75	GHe	A-302B		0.280	20
X-3M	75				0.280	20
X-3N	75				0.280	20
X-3O	75				0.280	20
X-3P	75	GHe	A-302B	Yes	0.280	20
X-1G	N/A	He	4340	No	0.370	21
X-1H	N/A	He	4340	No	0.370	21

*These specimens failed before or during the storage period.



NOTES:
1. All lines were 1/4 inch Super Pressure Line with Aminco High Pressure Fittings except as noted.
2. All lines from valves (8a) and (8b) to valve (9) and intensifier (22) were 1/4 inch AN.
3. – – – – – – to be installed for H_2 tests only
4. —— - —— to be installed for GHe or GN_2 tests only

Figure 7-1. Storage and Burst Test Setup

Table 7-2. Storage Pressure and Burst Test Equipment List

Item No.	Item	Manufacturer	Model/ Part No.	Serial No.	Remarks
1	Intensifier	American Instrument Co.	46-402 1M	EE66 68	
2a thru 2z, 2aa thru 2ah	Hand Valves	Autoclave	30VM-4071 G-316-CW HT-X604 63	N/A	1/4 inch, 30,000 psig
3a thru 3e	Hand Valves	Robbins	SSKG-250-4T	N/A	1/4 inch, 6000 psig
4a thru 4e	Hand Valves	Robbins	SSNA-250-4T	N/A	1/4 inch, 6000 psig
5	Hand Valve	Robbins	634960	N/A	1/4 inch, 6000 psig
6	Hand Valve	Tescom	30-1101-104	N/A	1/4 inch, 10,000 psig
7	Hand Valve	Whitey	1RS4	N/A	1/4 inch, 3000 psig
8a and 8b	Hand Valve	Airco	N/A	N/A	Shut-off valves furnished on K-bottles
9	Hand Valve	Grove	1/4 F16-10898K	N/A	1/4 inch, 6000 psig
10	Pressure Regulator	Grove	15-LH	L-32I 21	0-2000 psi
11	Vacuum Measurement System	N. R. C.	720	1119 09-V	Calibrated to Stokes-McCleod Gage. Ionization gage tubes Model 563-SK

Table 7-2. Storage Pressure and Burst Test Equipment List (Continued)

Item No.	Item	Manufacturer	Model/ Part No.	Serial No.	Remarks
12a	Pressure Transducer	B-L-H	SR-4	21283	0-30,000 psig, accuracy ±.5%
12b	Pressure Transducer	B-L-H	SR-4	21255	0-30,000 psig, accuracy ±.5%
12c	Pressure Transducer	B-L-H	SR-4	21291	0-30,000 psig, accuracy ±.5%
12d	Pressure Transducer	B-L-H	SR-4	18441	0-30,000 psig. accuracy ±.5%
12e	Pressure Transducer	B-L-H	SR-4	21270	0-30,000 psig, accuracy ±.5%
13	Pneumatic Filter	Hydro-dyne	31-2642	A002	10 micron nominal 25 micron absolute
14, 14a, and 14b	GN_2 Supply	N/A	N/A	N/A	Supply (14) to be used to purge vent lines when necessary
15	Pressure Gage	Heise	N/A	H44881	0-500 psig
16a and 16b	Hand Valves	Robbins	SSKG-3758-87	N/A	1/2 inch, 6000 psig
17	Pressure Gage	Ashcroft	N/A	035	0-200 psig, accuracy ±.5%
18	Pressure Gage	Heise	N/A	41242	0-30,000 psig, accuracy ±.2%
19	Vacuum Pump	Kenney	802-308	2070H E6095-50	

Table 7-2. Storage Pressure and Burst Test Equipment List (continued)

Item No.	Item	Manufacturer	Model/ Part No.	Serial No.	Remarks
20a	Thermocouple	BECO	N/A	N/A	Iron-Constantan
20b	Thermocouple	BECO	N/A	N/A	Iron-Constantan
20c	Thermocouple	BECO	N/A	N/A	Iron-Constantan
20d	Thermocouple	BECO	N/A	N/A	Iron-Constantan
20e	Thermocouple	BECO	N/A	N/A	Iron-Constantan
21	H2 Purifier	Milton Roy	C-50D	S-2502A	
22	Intensifier	Haskel	AGD-4	266-12	
23	Pressure Regulator	Marotta	LB-21	515	0-6000 psig
24a and 24b	Ullage Tanks	BECO	N/A	N/A	Stainless steel
25	Vacuum Pump	Diffusion	N/A	H112	
26	Helium Leak Detector	CEC	24-120A	7136	
27a thru 27e	Test Fixture	BECO	N/A	N/A	

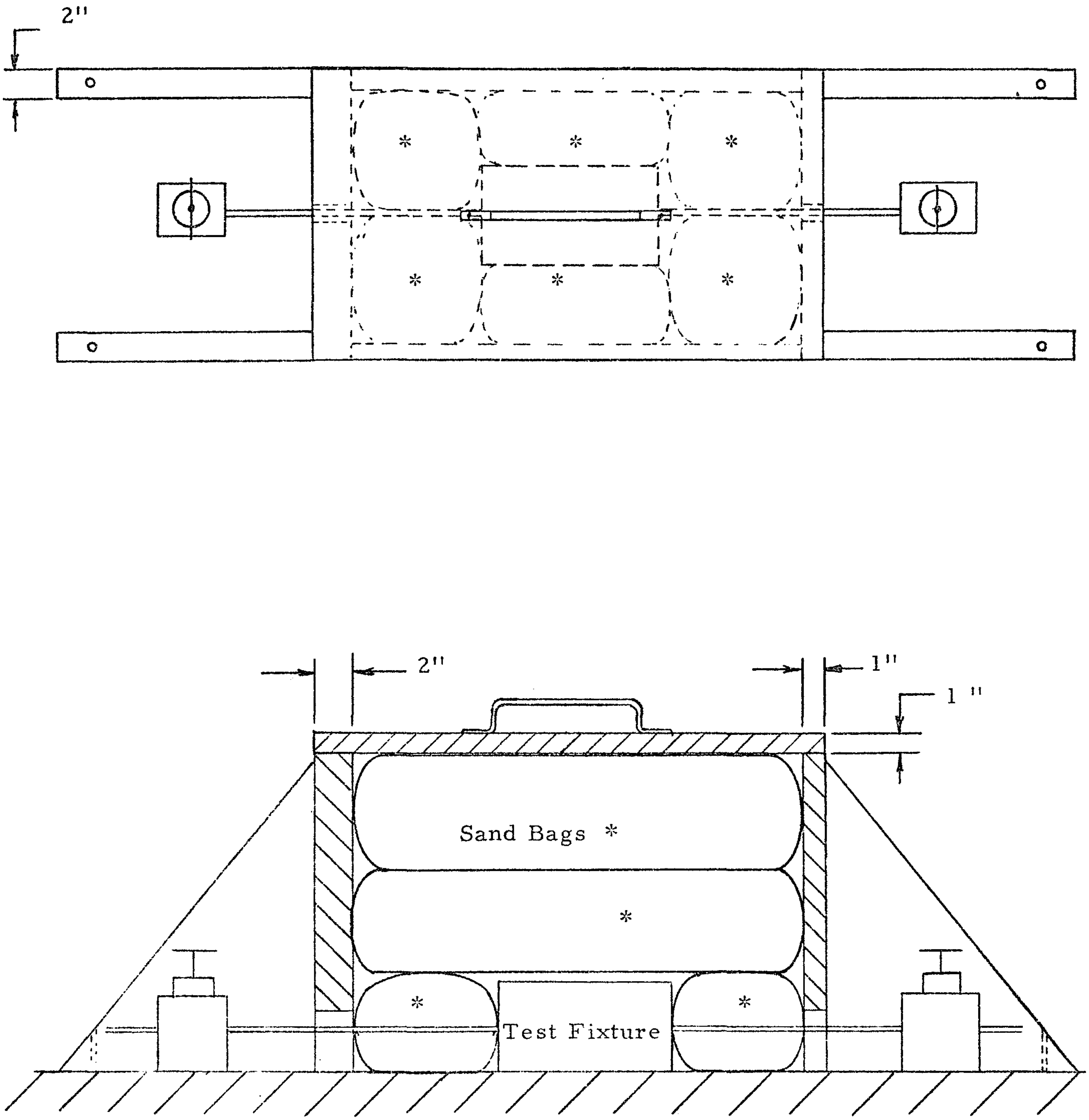


Figure 7-2. Typical Safety Setup

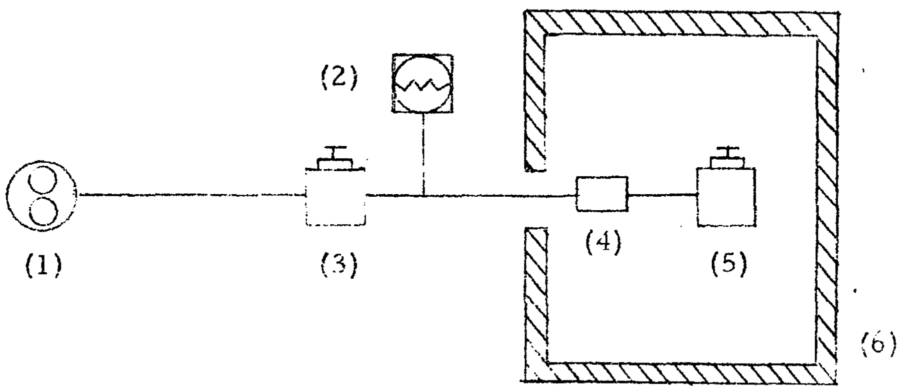


Figure 7-3. Hydraulic Oil Burst Test Setup

Table 7-3. Hydraulic Oil Burst Test Equipment List

Item No.	Item	Manufacturer	Model/ Part No.	Serial No.	Remarks
1	Hand Pump	Blackhawk	P-228	FK4Y74	0-20,000 psig
2	Pressure Transducer	BLH	GPCG	33553	0-20,000 psig Accuracy ±.5%
3	Hand Valve	Autoclave	30VM-4071-G-316-CW HT-X604 63	N/A	1/4 inch, 30,000 psig
4	Test Fixture	BECO	N/A	N/A	
5	Hand Valve	Autoclave	30VM-4071-G-316-CW HT-X604 63	N/A	1/4 inch, 30,000
6	Test Cell	N/A	N/A	N/A	

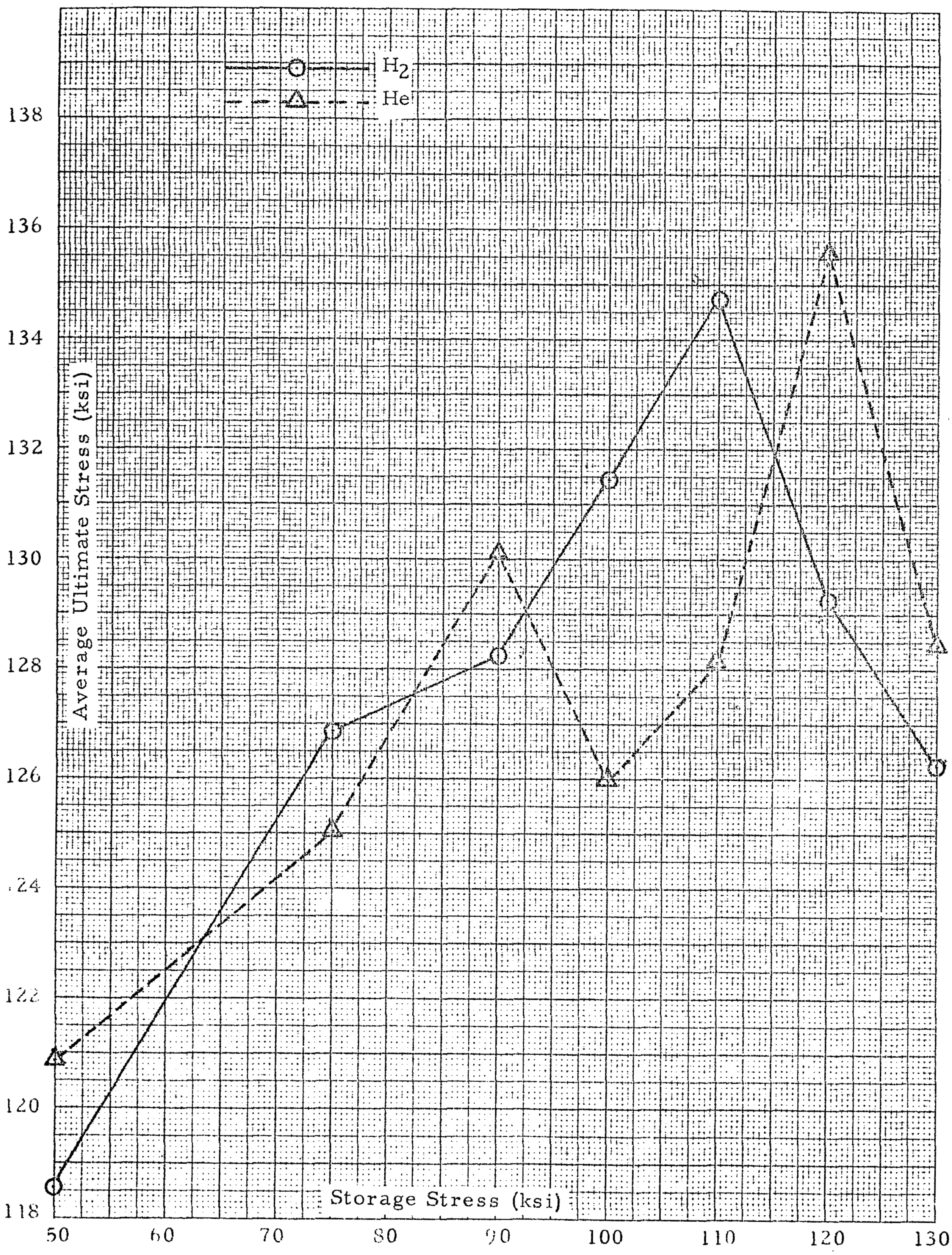


Figure 7-4. Average Ultimate Stress vs Storage Stress

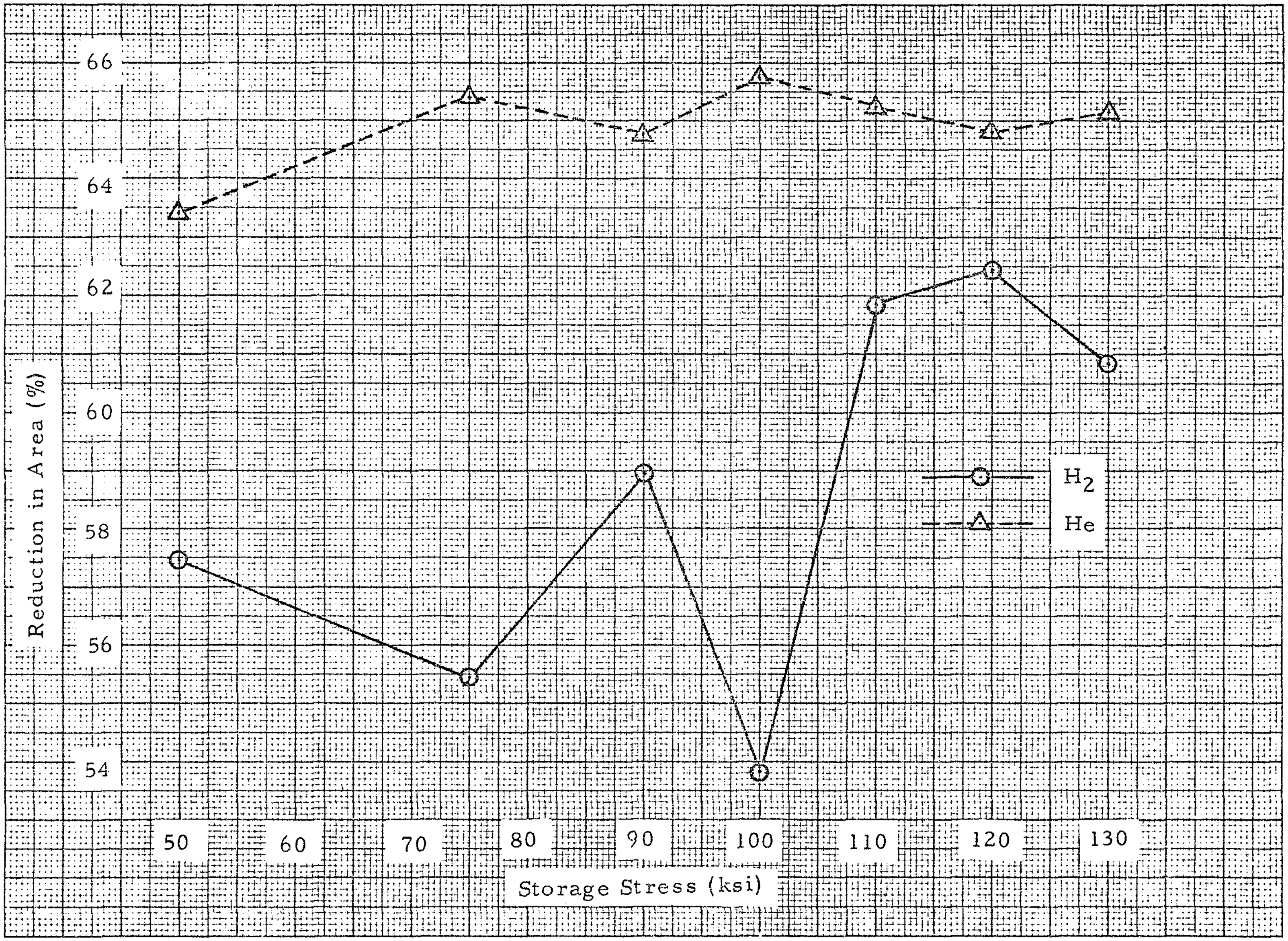


Figure 7-5 Average Reduction in Area vs Storage Stress

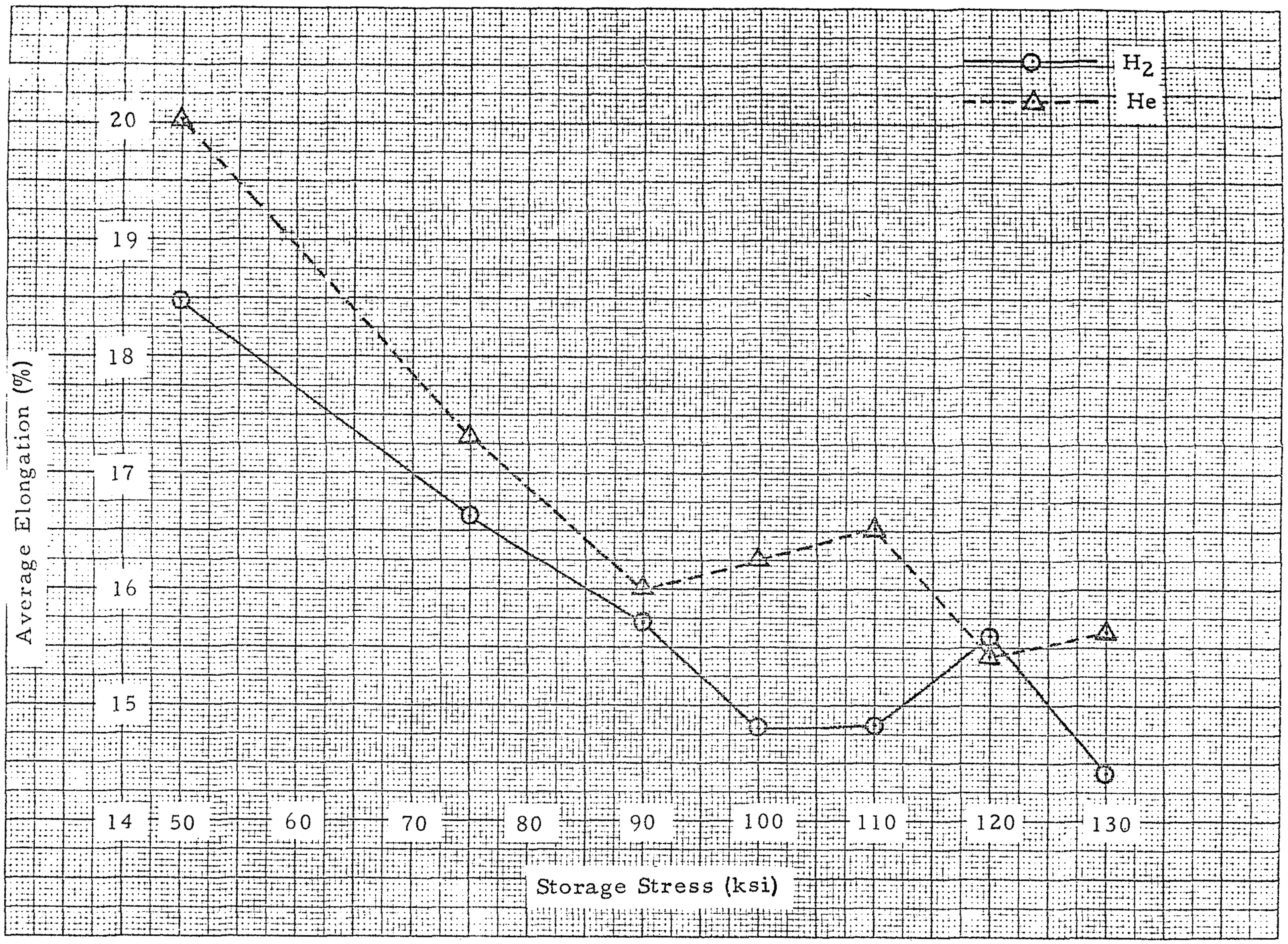


Figure 7-6. Average Elongation vs Storage Stress

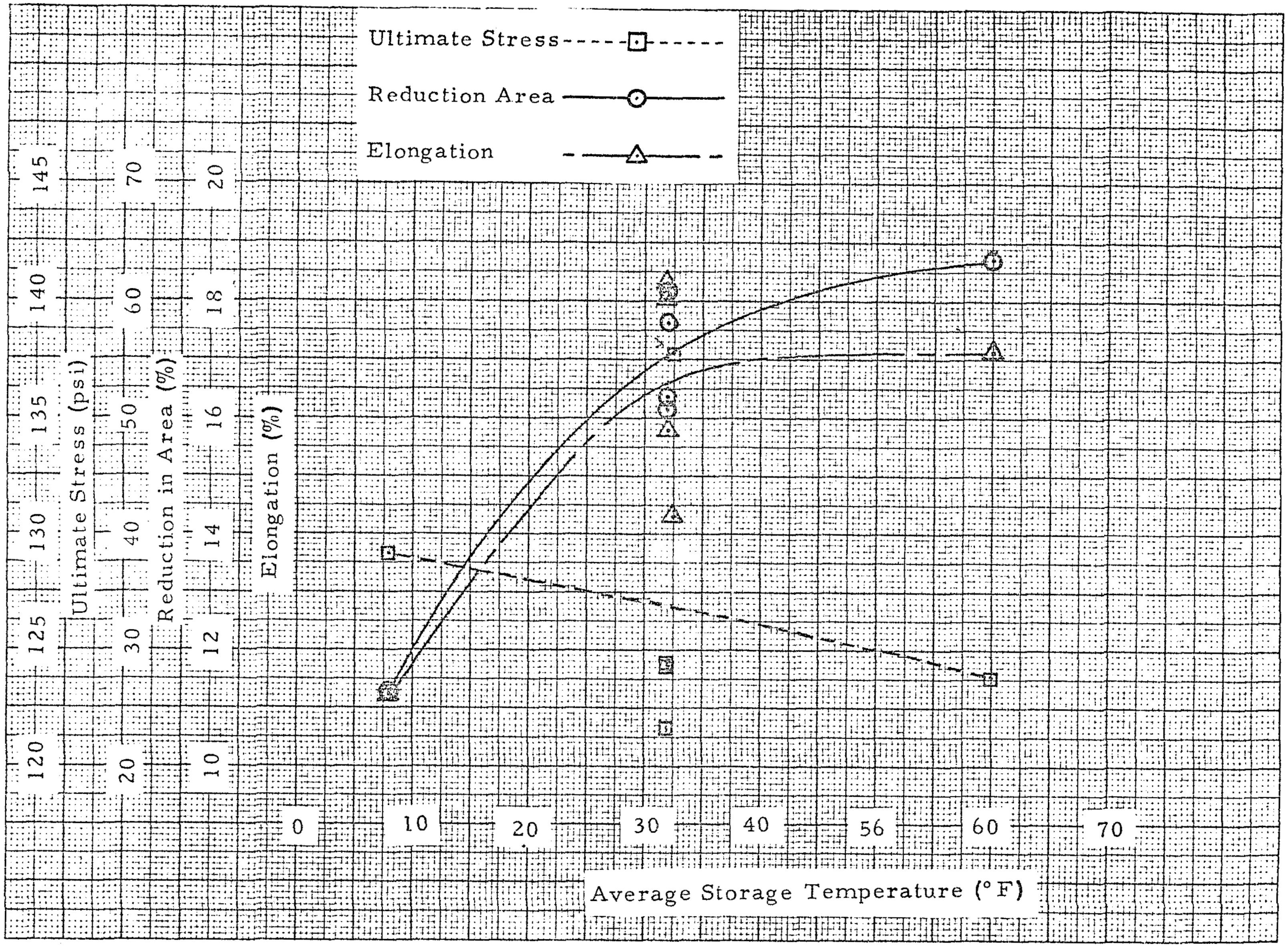


Figure 7-7. Average Storage Temperature vs Ultimate Stress, Reduction in Area and Elongation for X-3 Hydrogen Specimens

Table 7-4. Storage and Burst Test Data for X-2 H_2 Tensile Specimens

Specimen	Storage Time	Average Specimen Storage Temperature (° F)	Storage Stress (ksi)	Stress Increase (ksi/min)	Time to Failure (seconds)	Reduction in Area (%)	Elongation (%)	Ultimate Stress (psi)	Remarks
X-2A	29 Hr. 58 Min.	60	50	28.50	125	65.6	19.9	115,604	Due to leakage during storage, the stress at the start of the burst operation was 50,600 psi.
X-2B	24 Hr. 18 Min.	32	50	20.90	208	61.6	19.1	121,385	
X-2C	24 Hr. 8 Min.	32	50	23.40	175	49.0	16.5	117,173	
X-2D	24 Hr. 27 Min.	32	50	18.22	208	17.5	7.6	128,501	
X-2E	24 Hr. 6 Min.	65	50	29.30	110	65.2	20.1	119,524	
X-2K	24 Hr. 55 Min.	32	50	20.59	205	46.0	16.9	119,158	
Average	25 Hr.	44.2	50	24.54	164.6	57.48	18.49	118,569	Average - Does not include Specimen X-2D

Table 7-5. Storage and Burst Test Data for X-2 He Tensile Specimens

Specimen	Storage Time	Average Specimen Storage Temperature (° F)	Storage Stress (ksi)	Stress Increase (ksi/min)	Time to Failure (seconds)	Reduction in Area (%)	Elongation (%)	Ultimate Stress (psi)	Remarks
X-2F	24 Hr. 43 Min.	55	50	23.7	178	59.3	20.3	119,401	
X-2G	24 Hr. 49 Min	55	50	25.4	169	64.2	20.5	120,559	
X-2H	24 Hr. 33 Min.	55	50	25.6	172	63.0	19.8	122,335	
X-2I	24 Hr. 20 Min.	55	50	5.72	718	66.2	19.8	117,332	
X-2J	24 Hr. 5 Min.	55	50	26.5	189	64.5	19.8	124,812	
Average	24 Hr. 30 Min.	55	50	25.3	177	63.4	20.04	120,887	Average - The "time to failure and "stress increase rate" average does not include specimen X-2I.

Table 7-6. Storage and Burst Test Data for X-3 H_2 Tensile Specimens

Specimen	Storage Time	Average Specimen Storage Temperature (° F)	Storage Stress (ksi)	Stress Increase (ksi/min)	Time to Failure (seconds)	Reduction in Area (%)	Elongation (%)	Ultimate Stress (psi)	Remarks
X-3A	29 Hr. 39 Min.	60	75	57.60	74	63.6	17.12	123,790	Due to leakage during storage, the stress at the start of the burst operation was 63,200 psi.
X-3B	24 Hr. 43 Min.	32	75	15.58	208	50.9	15.8	121,730	Stress was increased to 118,200 psi, held for 5 minutes and then increased to burst.
X-3C	25 Hr. 27 Min.	8	75	4.04	916	26.5	11.25	129,078	Setup failure due to low temperature caused slow pressurzation rate.
X-3D	24 Hr. 19 Min.	32	75	13.71	247	58.1	18.3	124,277	
X-3E	24 Hr. 14 Min.	32	75	15.20	279	51.8	14.3	137,772	
X-3K	24 Hr. 7 Min.	32	75	20.25	166	60.9	18.1	123,792	

Table 7-6. Storage and Burst Test Data for X-3 H_2 Tensile Specimens (continued)

Specimen	Storage Time	Average Specimen Storage Temperature (°F)	Storage Stress (ksi)	Stress Increase (ksi/min)	Time to Failure (seconds)	Reduction in Area (%)	Elongation (%)	Ultimate Stress (psi)	Remarks
Average	25 Hr. 21 Min.	32	75	12.95	225	55.43	16.63	126,892	Average - Does not include specimens X-3C and X-3A.

Table 7-7. Storage and Burst Test Data for X-3 GN_2 Tensile Specimen

Specimen	Storage Time	Average Specimen Storage Temperature (°F)	Storage Stress (ksi)	Stress Increase (ksi/min)	Time to Failure (seconds)	Reduction in Area (%)	Elongation (%)	Ultimate Stress (psi)	Remarks
X-3F	24 Hr. 2 Min.	40	75	69.8	48	64.7	17.3	123,588	
X-3G	24 Hr. 5 Min.	40	75	63.9	66	63.5	16.6	138,584	
X-3H	24 Hr. 10 Min.	40	75	61.5	57	65.2	17.5	127,438	
X-3I	24 Hr. 13 Min.	40	75	72.4	56	61.6	15.6	134,409	
X-3J	24 Hr. 16 Min.	40	75	60.3	55	64.2	17.4	127,943	
Average	24 Hr. 9 Min.	40	75	65.58	56.4	63.84	16.88	130,394	

Table 7-8. Storage and Burst Test Data for X-3 He Tensile Specimens

Specimen	Storage Time	Average Specimen Storage Temperature (° F)	Storage Stress (ksi)	Stress Increase (ksi/min)	Time to Failure (seconds)	Reduction in Area (%)	Elongation (%)	Ultimate Stress (psi)	Remarks
X-3L	24 Hr. 11 Min.	66	75	74.7	46	68.5	18.6	124,868	
X-3M	24 Hr. 12 Min.	66	75	74.6	46	66.0	17.2	124,994	
X-3N	24 Hr. 2 Min.	66	75	69.8	51	59.2	16.2	126,844	
X-30	24 Hr. 10 Min.	66	75	65.5	51	66.2	18.6	123,170	
X-3P	24 Hr. 10 Min.	66	75	74.0	47	67.1	16.0	125,314	
Average	24 Hr. 9 Min.	66	75	71.72	48.2	65.4	17.32	125,038	

Table 7-9. Storage and Burst Test Data for X-4 H_2 Tensile Specimens

Specimen	Storage Time	Average Specimen Storage Temperature (° F)	Storage Stress (ksi)	Stress Increase (ksi/min)	Time to Failure (seconds)	Reduction in Area (%)	Elongation (%)	Ultimate Stress (psi)	Remarks
X-4A	29 Hr. 29 Min.	60	90	59.67	27	62.9	16.6	122,679	
X-4B	24 Hr. 7 Min.	48	90	51.46	39	59.4	15.4	129,383	
X-4C	24 Hr. 3 Min.	48	90	61.75	34	60.4	16.1	131,003	
X-4D	24 Hr. 9 Min.	65	90	54.95	36	58.2	15.4	129,329	
X-4E	24 Hr. 9 Min.	65	90	48.96	38	52.3	14.9	126,931	
X-4K	24 Hr. 10 Min.	65	90	48.66	42	60.5	15.9	130,028	
Average	24 Hr. 11 Min	58.5	90	54.24	36	58.95	15.72	128,225	

Table 7-10. Storage and Burst Test Data for X-4 He Tensile Specimens

Specimen	Storage Time	Average Specimen Storage Temperature (° F)	Storage Stress (ksi)	Stress Increase (ksi/min)	Time to Failure (seconds)	Reduction in Area (%)	Elongation (%)	Ultimate Stress (psi)	Remarks
X-4F	24Hr. 14 Min.	46	90	65.0	32	63.3	15.8	130,994	
X-4G	24 Hr. 17 Min.	46	90	59.8	32	65.9	16.3	128,223	
X-4H	24 Hr. 20 Min.	46	90	62.7	32	64.0	14.4	129,496.	
X-4I	24 Hr. 23 Min.	46	90	64.2	31	65.4	16.7	129,262	
X-4J	24 Hr. 26 Min.	46	90	64.2	34	65.3	16.8	132,534	
Average	24 Hr. 20 Min.	46	90	63.18	32.2	64.78	16.0	130,101	

Table 7-11. Storage and Burst Test Data for X-5 H_2 Tensile Specimens

Specimen	Storage Time	Average Specimen Storage Temperature (° F)	Storage Stress (ksi)	Stress Increase (ksi/min)	Time to Failure (seconds)	Reduction in Area (%)	Elongation (%)	Ultimate Stress (psi)	Remarks
X-5A	29 Hr. 16 Min.	60	100	42.34	26	63.1	16.9	120,854	Due to fixture leakage, stress at the start of burst operation was 85.2 ksi.
X-5B	24 Hr. 9 Min.	32	100	50.29	38	49.0	13.6	135,005	
X-5C	24 Hr. 12 Min.	32	100	58.89	27	63.4	16.1	129,079	
X-5D	24 Hr. 15 Min.	32	100	63.84	29	50.8	14.2	133,861	
X-5E	24 Hr. 18 Min.	32	100	71.43	21	60.1	16.2	127,663	
X-5K	24 Hr. 5 Min.	32	100	66.92	28	45.8	13.9	131,669	
Average	24 Hr. 12 Min.	32	100	62.27	28.6	53.82	14.8	131,455	Average does not include specimen X-5A.

Table 7-12. Storage and Burst Test Data for X-5 He Tensile Specimens

Specimen	Storage Time	Average Specimen Storage Temperature (° F)	Storage Stress (ksi)	Stress Increase (ksi/min)	Time to Failure (seconds)	Reduction in Area (%)	Elongation (%)	Ultimate Stress (psi)	Remarks
X-5F	24 Hr. 1 Min.	50	100	71.47	20	65.6	16.1	126,666	
X-5G	24 Hr. 4 Min.	50	100	63.58	22	66.6	16.2	126,300	
X-5H	24 Hr. 8 Min.	50	100	80.78	18	65.9	16.5	128,026	
X-5I	24 Hr. 11 Min.	50	100	-	19	64.5	16.2	-	Recorder failed to operate.
X-5J	24 Hr. 15 Min.	50	100	75.47	16	66.2	16.2	122,928	
Average	24 Hr. 7 Min.	50	100	72.83	19	65.76	16.24	125,980	

Table 7-13. Storage and Burst Test Data for X-6 H_2 Tensile Specimens

Specimen	Storage Time	Average Specimen Storage Temperature (° F)	Storage Stress (ksi)	Stress Increase (ksi/min)	Time to Failure (seconds)	Reduction in Area (%)	Elongation (%)	Ultimate Stress (psi)	Remarks
X-6A	28 Hr. 45 Min.	60	110	48.59	22	59.8	14.2	128,458	Due to fixture leakage, stress at the start of burst operation was 95.0 KSI.
X-6L	24 Hr. 7 Min.	66	110	60.99	19	63.7	15.6	129,832	
X-6M	24 Hr. 7 Min.	66	110	68.83	26	63.2	14.8	140,133	
X-6N	24 Hr. 7 Min.	66	110	68.51	18	64.1	15.9	131,048	
X-60	24 Hr. 8 Min.	66	110	75.16	24	60.8	14.4	140,651	
X-6P	24 Hr. 9 Min.	60	110	75.61	22	59.6	14.1	138,346	
Average	24 Hr. 8 Min	65	110	69.82	21.8	61.87	14.83	134,744	Average on "storage time", stress increase rate and time to failure" does not include specimen X-6A

Table 7-14. Storage and Burst Test Data for X-6 He Tensile Specimens

Specimen	Storage Time	Average Specimen Storage Temperature (° F)	Storage Stress (ksi)	Stress Increase (ksi/min)	Time to Failure (seconds)	Reduction in Area (%)	Elongation (%)	Ultimate Stress (psi)	Remarks
X-6F	24 Hr. 1 Min.	43	110	19.48	61	63.6	15.0	130,588	
X-6G	24 Hr. 0 Min.	43	110	28.34	31	65.6	17.5	125,516	
X-6H	24 Hr. 1 Min.	43	110	36.63	27	67.3	16.7	127,466	
X-6I	24 Hr. 1 Min.	43	110	30.82	30	66.6	17.8	126,274	
X-6J	24 Hr. 1 Min.	43	110	35.34	34	63.1	15.6	130,894	
Average	24 Hr. 1 Min.	43	110	30.12	36.6	65.24	16.52	128,147	

Table 7-15. Storage and Burst Test Data for X-6 Hydraulic Oil Tensile Specimens

Specimen	Storage Time	Average Specimen Storage Temperature (° F)	Storage Stress (ksi)	Stress Increase (ksi/min)	Time to Failure (seconds)	Reduction in Area (%)	Elongation (%)	Ultimate Stress (psi)	Remarks
X-6B	1 Hr.	-	110	159.14	5	65.6	16.1	124,077	
X-6C	1 Hr.	-	110	143.32	5	64.7	15.6	122,683	
X-6D	1 Hr.	-	110	174.11	5	62.5	14.0	125,324	
X-6E	1 Hr.	-	110	33.72	20	63.5	15.6	122,018	
X-6K	1 Hr.	-	110	152.43	5	66.6	17.1	123,430	
Average	1 Hr.	-	110	157.25	5	64.58	15.68	123,506	Average on "stress increase rate" and "time to failure" did not include specimen X-6E

Table 7-16. Storage and Burst Test Data for X-7 H_2 Tensile Specimens

Specimen	Storage Time	Average Specimen Storage Temperature (° F)	Storage Stress (ksi)	Stress Increase (ksi/min)	Time to Failure (seconds)	Reduction in Area (%)	Elongation (%)	Ultimate Stress (psi)	Remarks
X-7A	36 Min.	60	120	-	-	44.6	12.7	123,658	Specimen burst during storage. The specimen contained more than the normal amount of intermetallics.
X-7B	24 Hr. 7 Min.	65	120	64.10	7	63.8	17.2	128,288	
X-7C	24 Hr. 1 Min.	65	120	63.33	9	61.1	14.0	130,280	
X-7D	24 Hr. 7 Min.	65	120	-	-	-	-	-	Specimens X-7D, X-7E, and X-7K were removed from the test setup before burst. These were subjected to metallographic studies There was no evidence of hydrogen embrittlement.
X-7E	24 Hr. 5 Min.	65	120	-	-	-	-	-	
X-7K	24 Hr. 2 Min.	65	120	-	-	-	-	-	
Average	24 Hr. 4 Min.	65	120	63.72	8	62.45	15.60	129,284	Average (Specimen X-7B and X-7C)

Table 7-17. Storage and Burst Test Data for X-7 He Tensile Specimens

Specimen	Storage Time	Average Specimen Storage Temperature (° F)	Storage Stress (ksi)	Stress Increase (ksi/min)	Time to Failure (seconds)	Reduction in Area (%)	Elongation (%)	Ultimate Stress (psi)	Remarks
X-7F	24 Hr. 2 Min.	44	120	32.32	15	66.5	15.9	128,871	
X-7G	24 Hr. 2 Min.	44	120	36.33	38	64.7	16.0	144,726	
X-7H	24 Hr. 2 Min.	44	120	37.67	36	63.6	15.0	143,481	
X-7I	24 Hr. 2 Min.	44	120	35.79	14	65.3	15.1	129,633	
X-7J	24 Hr. 4 Min.	44	120	30.97	21	63.9	15.1	131,267	
Average	24 Hr. 2 Min.	44	120	34.62	24.8	64.80	15.42	135,595	

Table 7-18. Storage and Burst Test Data for X-8 H_2 Tensile Specimens

Specimen	Storage Time	Average Specimen Storage Temperature (° F)	Storage Stress (ksi)	Stress Increase (ksi/min)	Time to Failure (seconds)	Reduction in Area (%)	Elongation (%)	Ultimate Stress (psi)	Remarks
X-8B	-	-	-	-	-	64.8	15.1	129,427	Failed before storage pressure was reached.
X-8C	-	-	-	-	-	63.6	14.3	124,955	Failed before storage pressure was reached.
X-8D	-	-	-	-	-	54.0	13.3	123,911	Failed before storage pressure was reached.
X-8E	-	-	-	-	-	60.9	13.8	126,892	Failed before storage pres-sure was reached.
X-8K	-	-	-	-	-	63.8	15.6	125,941	Failed before storage pres-sure was reached.
Average	-	-	-	-	-	61.42	14.42	126,225	

Table 7-19. Storage and Burst Test Data for X-8 He Tensile Specimens

Specimen	Storage Time	Average Specimen Storage Temperature (° F)	Storage Stress (ksi)	Stress Increase (ksi/min)	Time to Failure (seconds)	Reduction in Area (%)	Elongation (%)	Ultimate Stress (psi)	Remarks
X-8F	-	-	-	-	-	65.9	16.0	129,300	Failed before storage pressure was reached.
X-8G	-	-	-	-	-	66.4	16.9	126,606	Failed before storage pressure was reached.
X-8H	-	-	-	-	-	63.1	15.3	129,943	Failed before storage pressure was reached.
X-8I	-	-	-	-	-	64.3	16.2	125,950	Failed before storage pressure was reached.
X-8J	2 Hr. 11 Min.	-	130	-	-	63.2	13.8	129,427	Failed after 2 Hr. 11 Min. of storage.
Average			-	-	-	64.58	15.64	128,245	

Table 7-20. True Fracture Strength for Specimens Tested With Hydrogen

Specimen	True Fracture* Strength (psi)	Specimen	True Fracture* Strength (psi)
X-2A	335, 945	X-5B	265, 285
X-2B	312, 639	X-5C	356, 232
X-2C	229, 659	X-5D	272, 916
X-2D	155, 743	X-5E	319, 732
X-2E	343, 276	X-5K	243, 127
X-2K	220, 442	X-6A	319, 218
X-3A	339, 308	X-6L	356, 649
X-3B	248, 087	X-6M	379, 901
X-3C	175, 546	X-6N	365, 362
X-3D	296, 401	X-6O	359, 504
X-3E	285, 877	X-6P	343, 790
X-3K	319, 383	X-7A	223, 321
X-4A	330, 620	X-7B	354, 716
X-4B	316, 105	X-7C	334, 038
X-4C	330, 992	X-8B	367, 573
X-4D	309, 484	X-8C	343, 251
X-4E	266, 174	X-8D	269, 259
X-4K	324, 290	X-7E	324, 336
X-5A	328, 602	X-8K	347, 345

*Formula: $s = \frac{D1^2}{D2^2} \times S$

Where: s= True Fracture Strength (psi)
D1= Original Specimen Diameter (inch)
D2= Specimen Necked Down Diameter (inch)
S= Ultimate Stress (psi)

Table 7-21. True Fracture Strength for Specimens Tested with Media Other Than Hydrogen

Specimen	True Fracture Strength (psi)	Specimen	True Fracture Strength (psi)
X-2F	292, 891	X-5H	376, 012
X-2G	336, 601	X-5J	363, 498
X-2H	331, 039	X-6B**	360, 816
X-2I	348, 124	X-6C**	346, 457
X-2J	351, 595	X-6D**	333, 988
X-3F*	350, 866	X-6E**	334, 695
X-3G*	379, 304	X-6F	358, 203
X-3H*	350, 582	X-6G	365, 001
X-3I*	347, 985	X-6H	387, 624
X-3J*	358, 215	X-6I	378, 569
X-3L	396, 581	X-6J	353, 676
X-3M	367, 732	X-6K**	370, 043
X-3N	310, 007	X-7F	384, 938
X-3O	363, 475	X-7G	410, 298
X-3P	379, 075	X-7H	396, 725
X-4F	357, 876	X-7I	373, 991
X-4G	374, 796	X-7J	363, 872
X-4H	358, 963	X-8F	379, 754
X-4I	383, 650	X-8G	378, 172
X-4J	382, 626	X-8H	350, 846
X-5F	369, 231	X-8I	351, 778
X-5G	378, 647	X-8J	350, 747

*Tested with GN_2

**Tested with MIL-H-5606 hydraulic fluid.

All other specimens were tested with GHe.

Table 7-22. Oxygen Content of Hydrogen During Storage and Burst

Specimen	Oxygen Content During Storage and Burst (ppb)	Specimen	Oxygen Content During Storage and Burst (ppb)
X-1A	<50	X-4K	<60
X-1B	<50	X-5A	*
X-1C	<50	X-5B	<75
X-2A	*	X-5C	<75
X-2B	<55	X-5D	<75
X-2C	<55	X-5E	<75
X-2D	<55	X-5K	<75
X-2E	<60	X-6A	*
X-2K	<55	X-6L	<70
X-3A	*	X-6M	<40
X-3B	<70	X-6N	<50
X-3C	<80	X-60	<40
X-3D	<70	X-6P	<40
X-3E	<70	X-7A	<60
X-3K	<70	X-7B	<35
X-4A	*	X-7C	<40
X-4B	<70	X-8B	<40
X-4C	<70	X-8C	<40
X-4D	<60	X-8D	<60
X-4E	<60	X-8E	<30
		X-8K	<60

* Purification equipment was not available at the time these specimens were tested.

SECTION VIII

TENSILE TEST

A. TEST REQUIREMENTS

1. The specimens and fixture were to be dimensionally inspected for conformance to Figure 8-1. The specimen diameter (Dimension "A", Figure 8-1) was to be recorded, within $\pm$0.0001 inches, at the minimum value.

2. Each specimen was to be identified for future reference.

3. The specimens were to be secured and a tensile load applied until specimen failure.

4. Percent elongation, reduction in area and ultimate strength were to be tabulated. Stress-strain diagrams showing yield point and ultimate strength were to be developed.

B. TEST PROCEDURE

1. After machining of the specimens and fixtures was complete, a dimensional inspection was performed to insure conformance to the requirements of Figure 8-1. All applicable data was recorded.

2. Each specimen was inspected to insure that the specimen was identified as shown on Figure 8-1.

3. Each specimen was tested on a universal testing machine (Table 8-1) as follows:

   a. The specimen was installed in the universal testing machine.

   b. The specimen was loaded until failure at a displacement rate of .004 to .005 inch per minute. All applicable data was recorded.

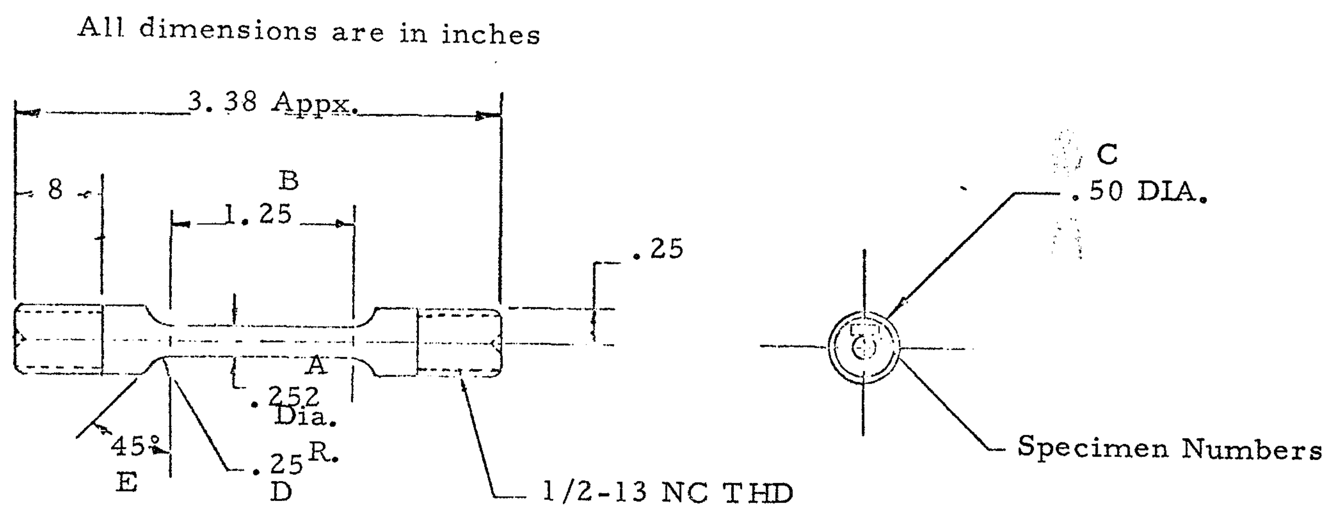


Figure 8-1. Tensile Specimen Physical Dimensions

Table 8-1. Tensile Test Equipment List

Item No.	Item	Manufacturer	Model/ Part No.	Serial No.	Remarks
1	Universal Testing Machine	Riehle	TS-60	R-46578	
2	Extensometer	Riehle	GN-20	N/A	
3	Specimen	BECO	N/A	N/A	
4	Specimen Adapter	BECO			

C. TEST RESULTS

1. The specimen dimensions were within tolerance except dimension B (Figure 8-1). This discrepancy was not considered detrimental, therefore testing was continued.

2. The yield strength of the X-Axis specimens ranged from 107,500 psi to 122,400 psi. The average yield strength was 112,600 psi. The ultimate stress ranged from 125,900 psi to 134,800 psi. The average ultimate stress was 130,090 psi.

3. The yield strength of the Y-Axis specimens ranged from 106,800 psi to 110,500 psi. The average yield strength was 108,700 psi. The ultimate stress ranged from 122,800 psi to 125,800 psi. The average ultimate stress was 124,700 psi.

4. The yield strength of the Z-Axis specimens ranged from 103,700 psi to 119,400 psi. The average yield strength was 110,800 psi. The ultimate stress ranged from 123,000 psi to 135,400 psi. The average ultimate stress was 127,640 psi.

5. The average elongation and reduction of area for the X-Axis specimens was 22.1% and 60.6% respectively. The average elongation and reduction of area for the Y-Axis specimens was 6.1% and 11.8% respectively. The average elongation and reduction of area for the Z-Axis specimens was 20.7% and 55.6% respectively.

6. The X-Axis and Z-Axis specimens failed with a typical cup and cone rupture. The Y-Axis specimens failed with a non-typical rough rupture with very little necking down effect. Typical ruptures for each axis are shown in Figures 8-2 and 8-3.

D. TEST DATA

The test data are presented in Tables 8-2, 8-3, 8-4, 8-5, 8-6 and 8-7. Plots of average stress vs strain for each axis are presented in Figures 8-4, 8-5, and 8-6. Figure 8-7 presents a plot of average stress vs strain for all specimens. Stress-strain curves for the individual specimens are presented in Figures C-1 through C-44 of Appendix C.

Table 8-2. Inspection Data for X-Specimens

Specimen	Dimension Designation and Specification				
	A (inch)	B (inch)	C (inch)	D (inch)	E (degrees)
	.252 ±.0005	1.25 +.06 -.00	.50 Dia.	.25 Rad.	45
X-1	.2521	1.315	.494	.25	45
X-2	.2518	1.400	.495	.25	45
X-3	.2517	1.400	.494	.25	45
X-4	.2520	1.345	.494	.25	45
X-5	.2518	1.390	.496	.25	45
X-6	.2521	1.395	.494	.25	45
X-7	.2520	1.370	.495	.25	45
X-8	.2518	1.390	.495	.25	45
X-9	.2510	1.315	.494	.25	45
X-10	.2520	1.290	.496	.25	45
X-11	.2523	1.400	.497	.25	45
X-12*	-	-	-	-	-
X-13	.2517	1.385	.496	.25	45
X-14	.2521	1.390	.494	.25	45
X-15	.2523	1.350	.493	.25	45

* Specimen X-12 was not tested.

Table 8-3. Inspection Data for Y-Specimens

Speci-men	Dimension Designation and Specification				
	A (inch) .252 ±.0005	B (inch) 1.25 +.06 -.00	C (inch) .50 Dia.	D (inch) .25 Rad.	E (degrees) 45
Y-1	.2520	1.390	.493	.25	45
Y-2	.2518	1.385	.495	.25	45
Y-3	.2529	1.375	.495	.25	45
Y-4	.2520	1.355	.494	.25	45
Y-5	.2518	1.370	.496	.25	45
Y-6	.2522	1.338	.496	.25	45
Y-7	.2521	1.350	.493	.25	45
Y-8	.2522	1.365	.493	.25	45
Y-9	.2521	1.375	.496	.25	45

Table 8-4. Inspection Data for Z-Specimens

Specimen	Dimension Designation and Specification				
	A (inch) .252 ±.0005	B (inch) 1.25 +.06 -.00	C (inch) .50 Dia.	D (inch) .25 Rad.	E (degrees) 45
Z-1	.2515	1.375	.495	.25	45
Z-2	.2522	1.390	.494	.25	45
Z-3	.2524	1.400	.493	.25	45
Z-4	.2517	1.400	.490	.25	45
Z-5	.2520	1.280	.495	.25	45
Z-6	.2522	1.400	.493	.25	45
Z-7	.2516	1.400	.493	.25	45
Z-8	.2519	1.390	.494	.25	45
Z-9	.2517	1.385	.493	.25	45
Z-10	.2521	1.400	.493	.25	45
Z-11	.2524	1.390	.492	.25	45
Z-12	.2522	1.395	.494	.25	45
Z-13	.2510	1.370	.498	.25	45
Z-14	.2529	1.295	.479	.25	45
Z-15	.2528	1.350	.496	.25	45

Table 8-5. Tensile Test Results, X-Axis

Specimen Number	Yield Strength (0.2% Elong) psi	Ultimate Stress (psi)	% Elongation	% Reduction of Area	Remarks
X-1	113,500	128,900	21.5	63	
X-2	107,500	125,900	22	60	
X-3	113,300	131,400	22	60	
X-4	109,100	126,900	22	60	
X-5	120,500	134,500	22	57	
X-6	112,000	128,800	22	59	
X-7	107,800	135,500	22	60	
X-8	112,000	130,000	22	60	
X-9	108,000	126,500	22	57	
X-10	119,500	133,100	23	65	
X-11	110,300	127,500	22	60	
X-13	111,500	129,200	22	61	
X-14	109,200	128,200	23	63	
X-15	122,400	134,800	22	63	
Average "X"	112,600	130,090	22.1	60.6	

Table 8-6. Tensile Test Results, Y-Axis

Specimen Number	Yield Strength (0.2% Elong) psi	Ultimate Stress (psi)	% Elongation	% Reduction of Area	Remarks
Y-1	110,500	124,800	6	16	
Y-2	109,600	125,000	5	9	Rupture occurred outside of gage marks
Y-3	106,900	123,600	5	9	Rupture occurred outside of gage marks
Y-4	109,100	122,800	6	9	
Y-5	108,900	125,200	6	10	Rupture occurred outside of gage marks
Y-6	109,000	125,200	6	15	Rupture occurred outside of gage marks
Y-7	109,000	125,600	6	12	Rupture occurred outside of gage marks
Y-8	109,500	125,800	7	15	Rupture occurred outside of gage marks
Y-9	106,800	124,900	8	11	
Average "Y"	108,700	124,700	6.1	11.8	

Table 8-7. Tensile Test Results, Z-Axis

Specimen Number	Yield Strength (0.2% Elong) psi	Ultimate Stress (psi)	% Elongation	% Reduction of Area	Remarks
Z-1	112,000	129,300	21	59	
Z-2	104,700	123,600	22	57	
Z-3	109,500	128,800	20	52	
Z-4	109,000	126,900	22	52	
Z-5	119,400	127,800	22	56	
Z-6	112,500	128,400	22	55	
Z-7	105,800	123,500	21	57	
Z-8	109,800	128,000	21	55	
Z-9	108,300	126,900	21	56	
Z-10	118,200	133,100	22	58	
Z-11	110,000	126,600	21	57	
Z-12	103,700	123,000	21	56	
Z-13	109,200	127,000	14	55	Rupture occurred at gage mark
Z-14	108,500	126,200	20	55	
Z-15	121,900	135,400	21	54	
Average "Z"	110,800	127,640	20.7	55.6	

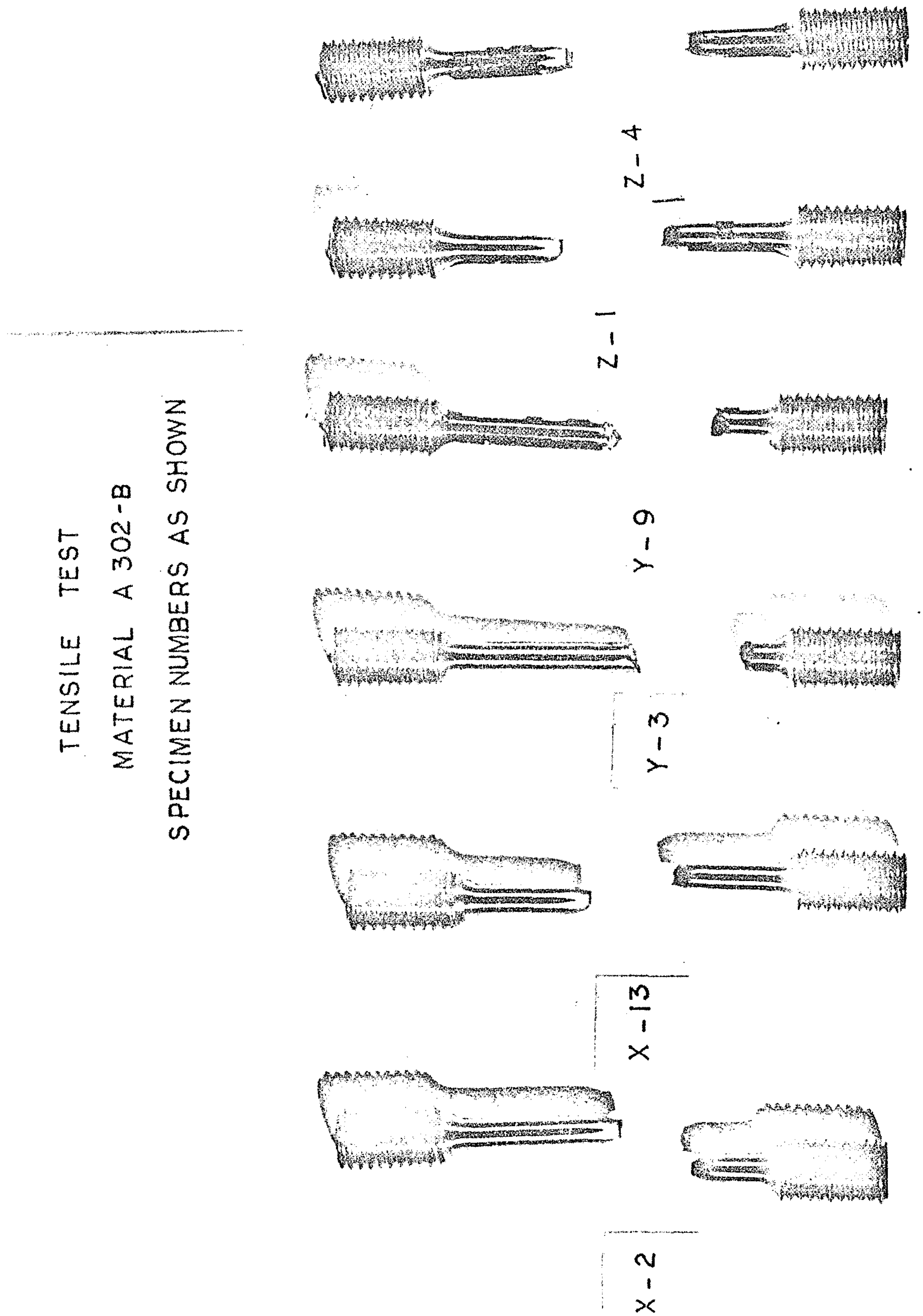


Figure 8-2. Typical Ruptures for "X", "Y" and "Z" Specimens

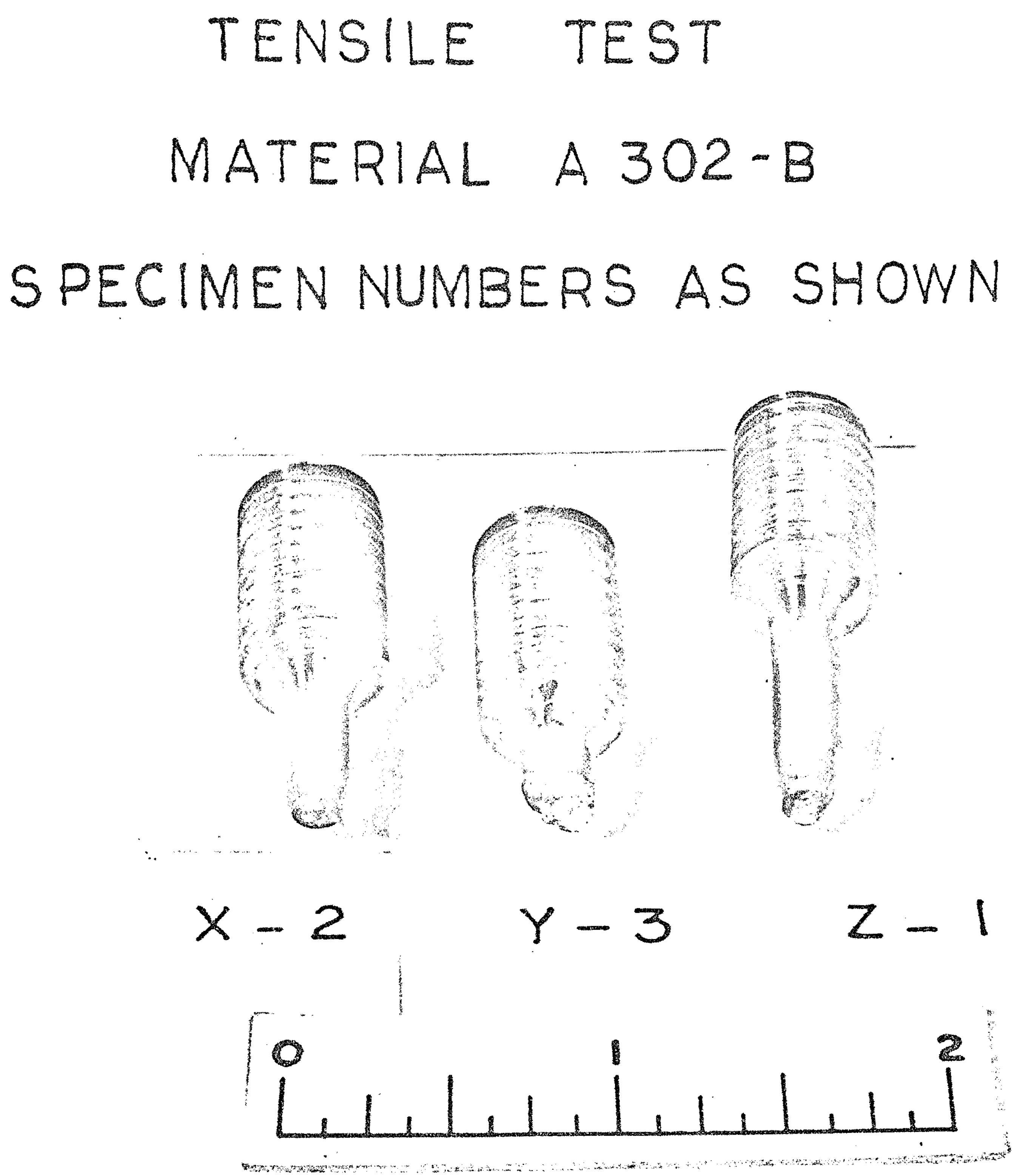


Figure 8-3. Illustration of Cup-Cone Rupture for X and Z Specimens and Non-Typical Break for Y Specimens

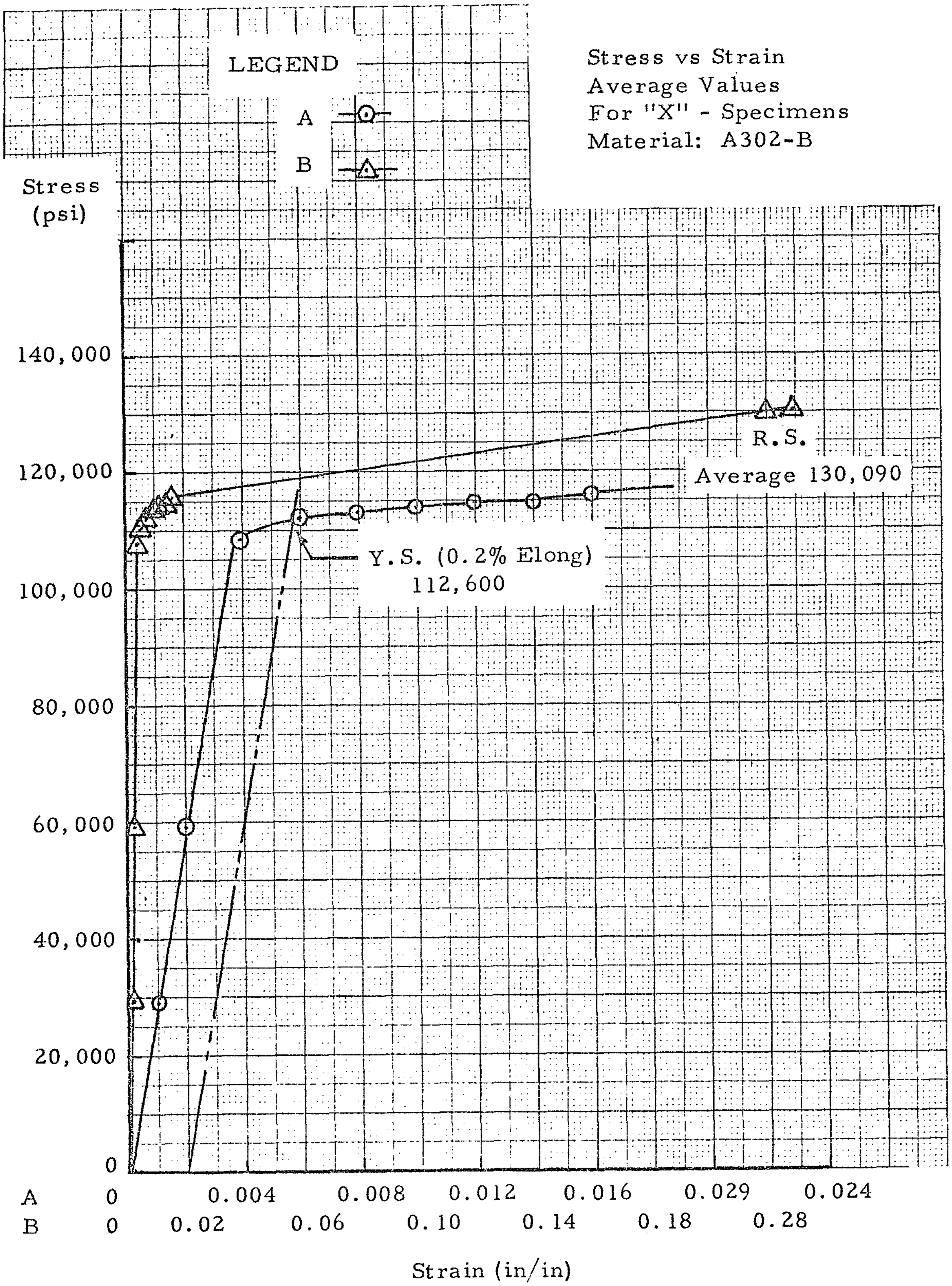


Figure 8-4. Average Stress vs Strain (X - Specimens)

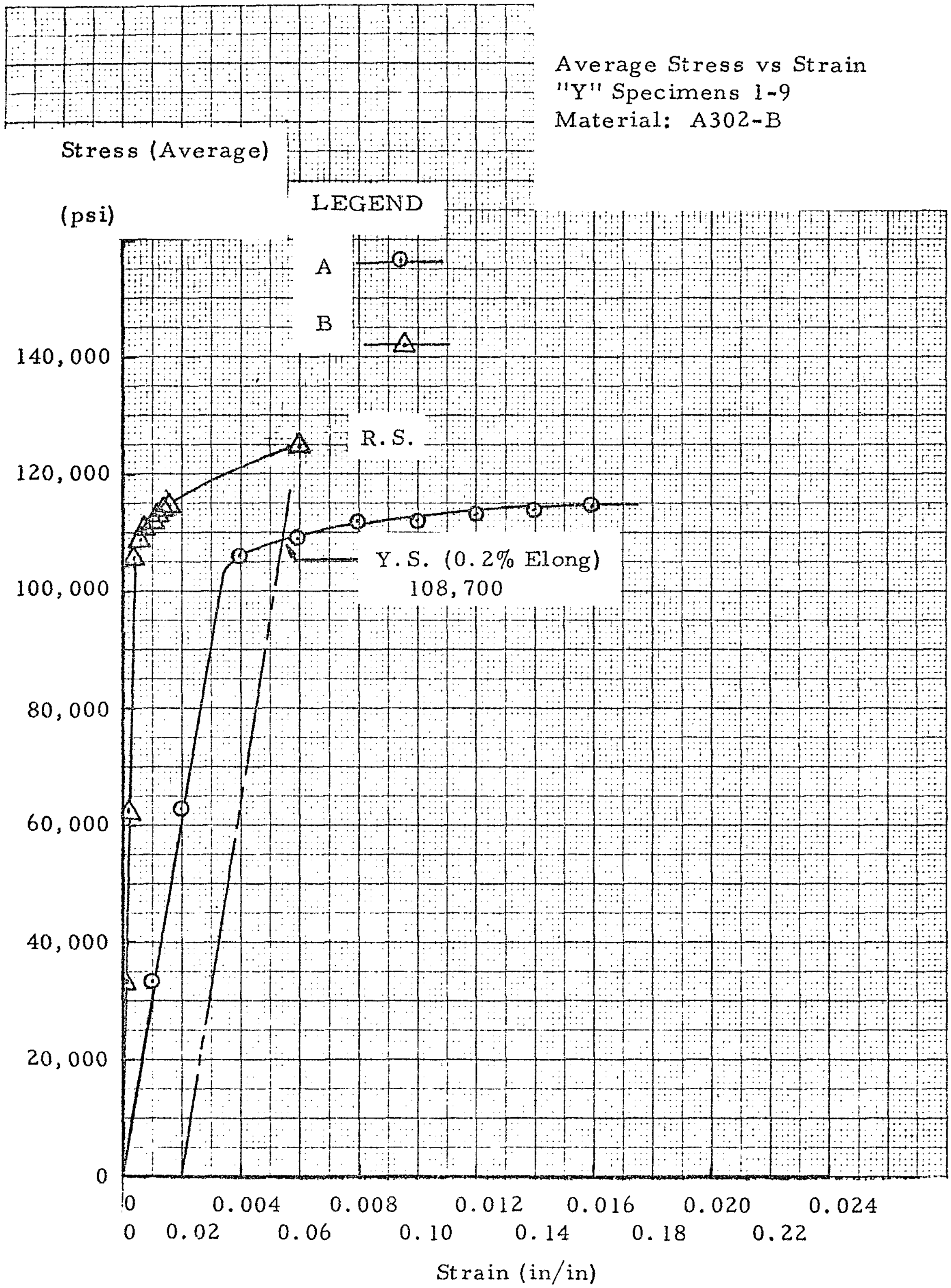


Figure 8-5. Average Stress vs Strain (Y - Specimens)

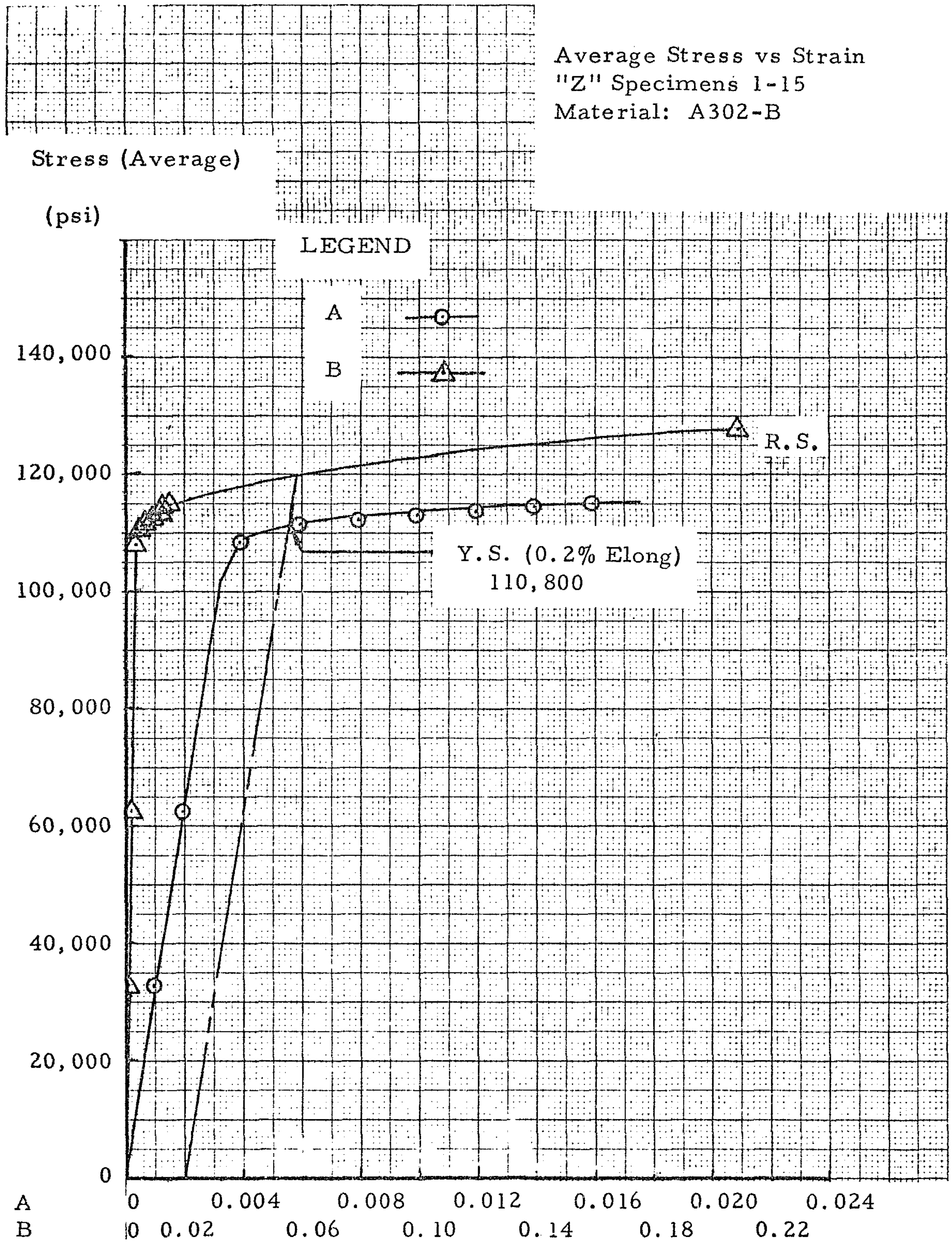


Figure 8-6. Average Stress vs Strain (Z- Specimens)

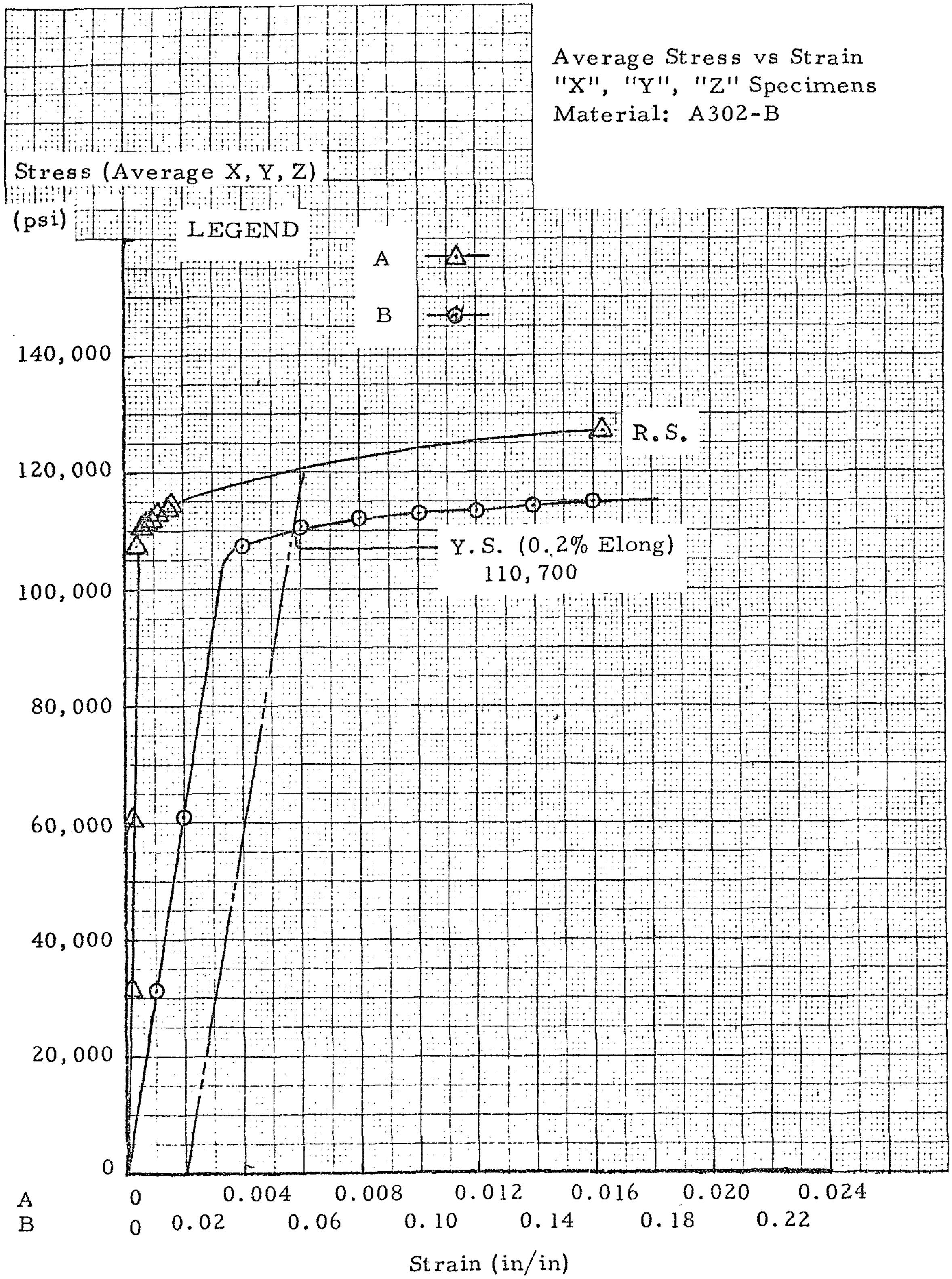


Figure 8-7. Average Stress vs Strain (All Specimens)

APPENDIX A

"TALYROND" CONCENTRICITY CURVES FOR THIN WALL CYLINDERS

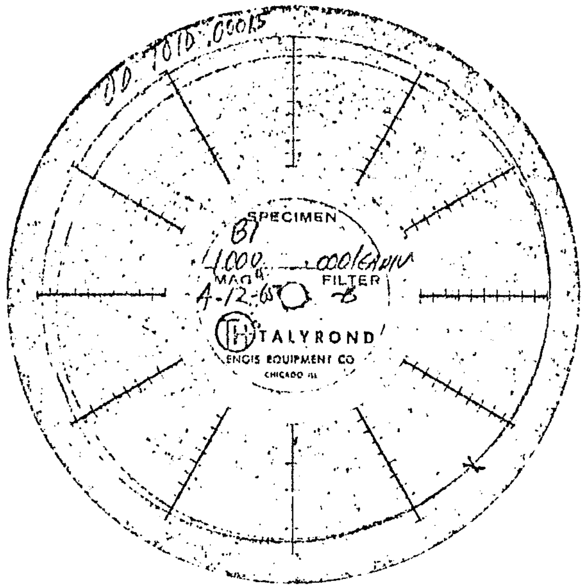


Figure 2-2, Specimen No. B-1

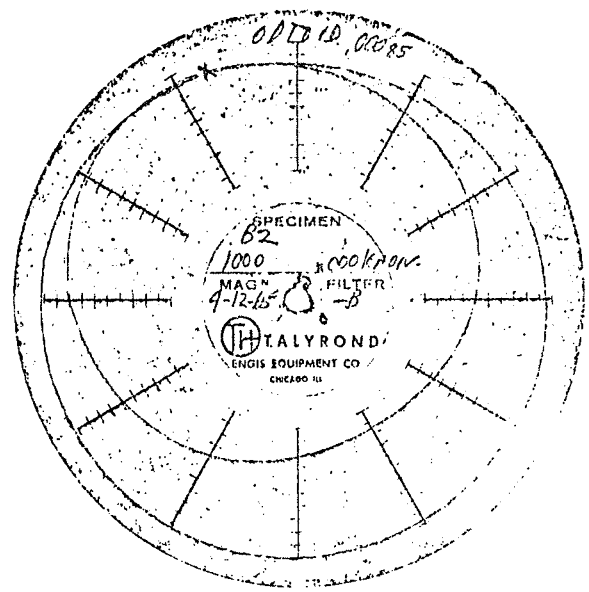


Figure 2-3, Specimen No. B-2

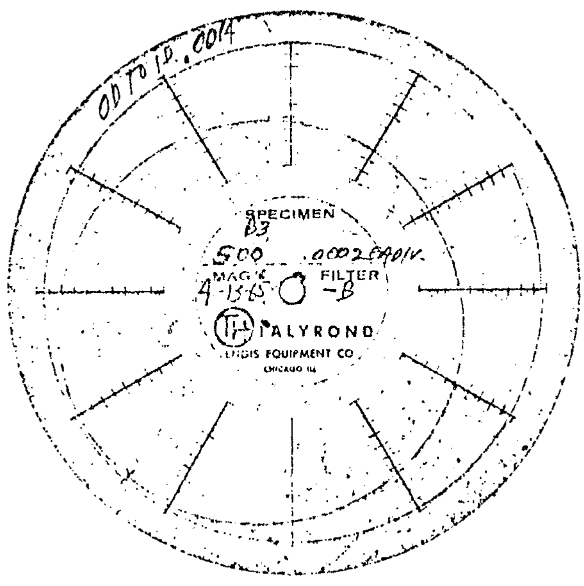


Figure 2-4, Specimen No. B-3

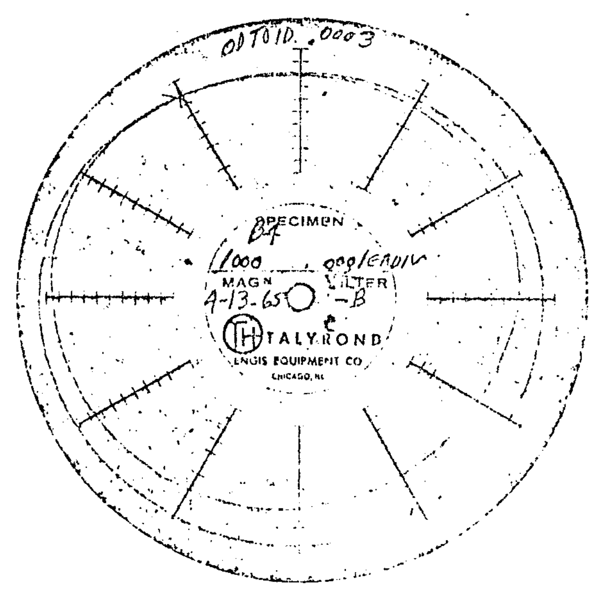


Figure 2-5, Specimen No. B-4

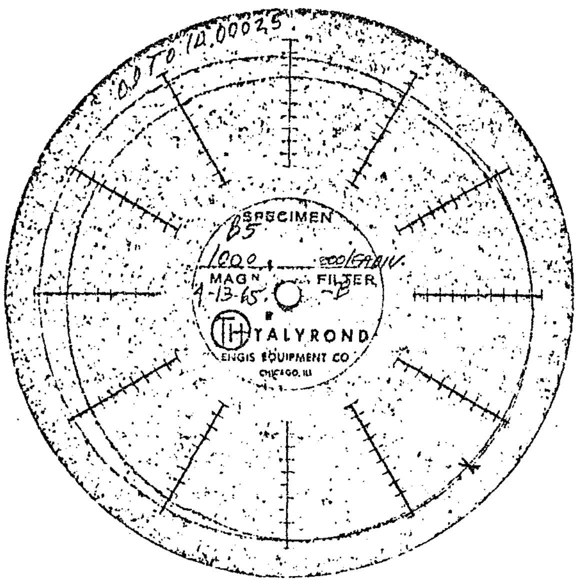


Figure 2-6, Specimen No. B-5

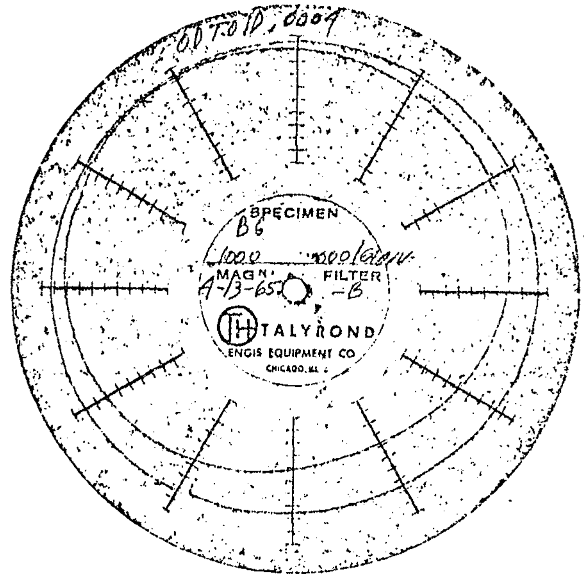


Figure 2-7, Specimen No. B-6

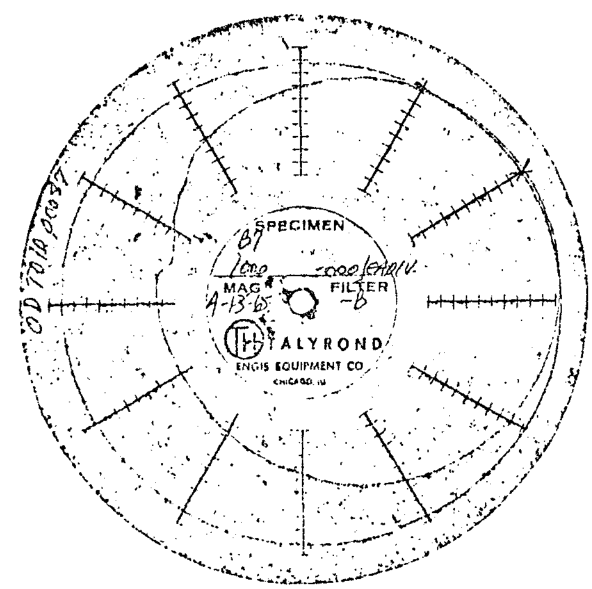


Figure 2-8, Specimen No. B-7

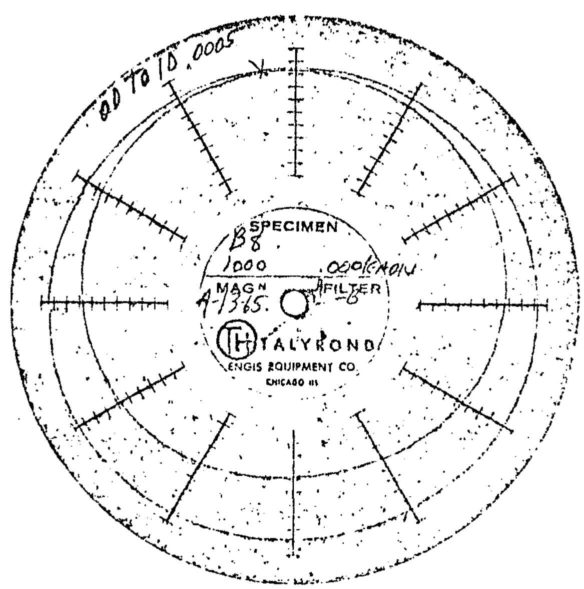


Figure 2-9, Specimen No. B-8

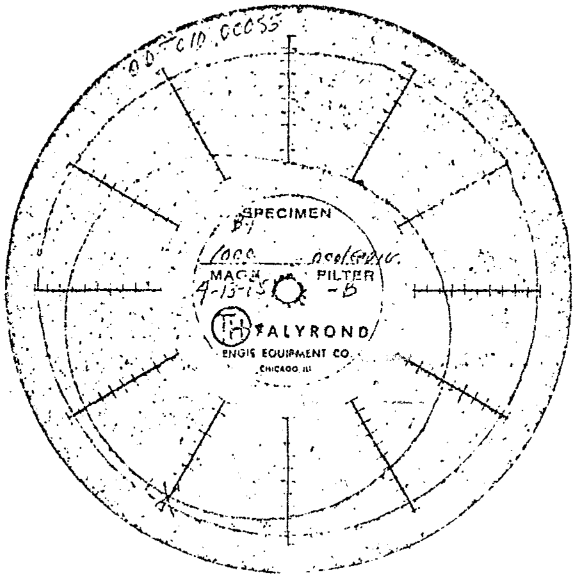


Figure 2-10, Specimen No. B-9

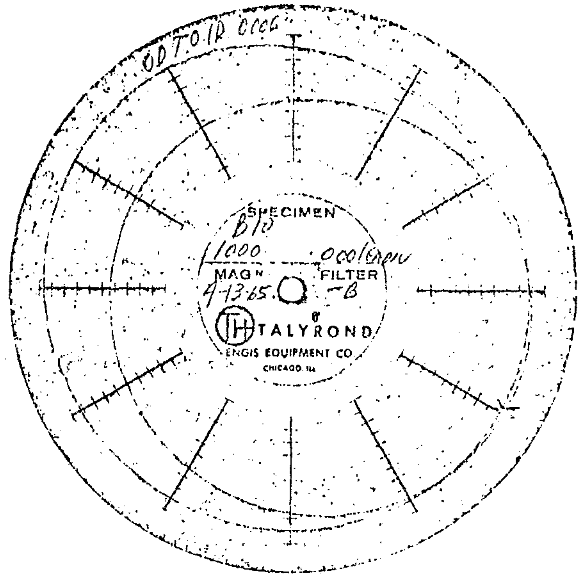


Figure 2-11, Specimen No. B-10

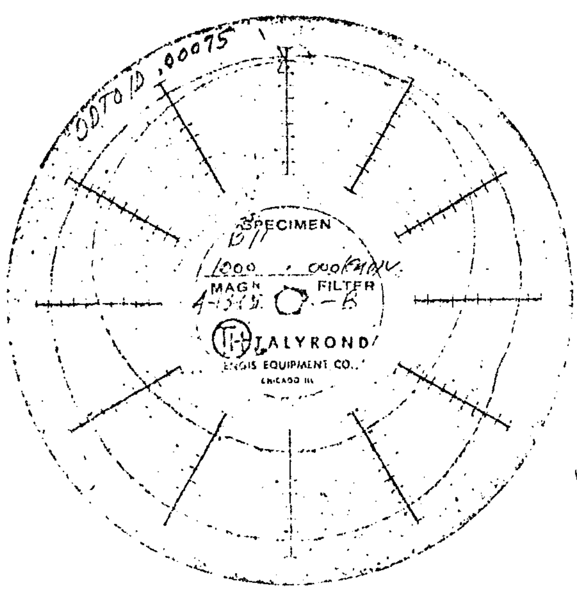


Figure 2-12, Specimen No. B-11

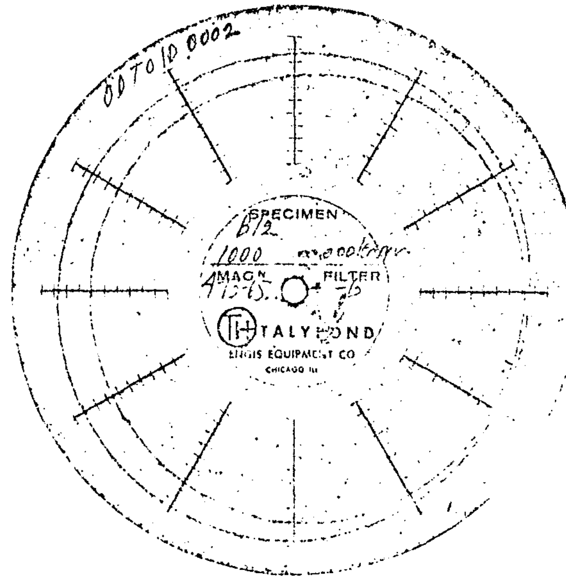


Figure 2-13, Specimen No. B-12

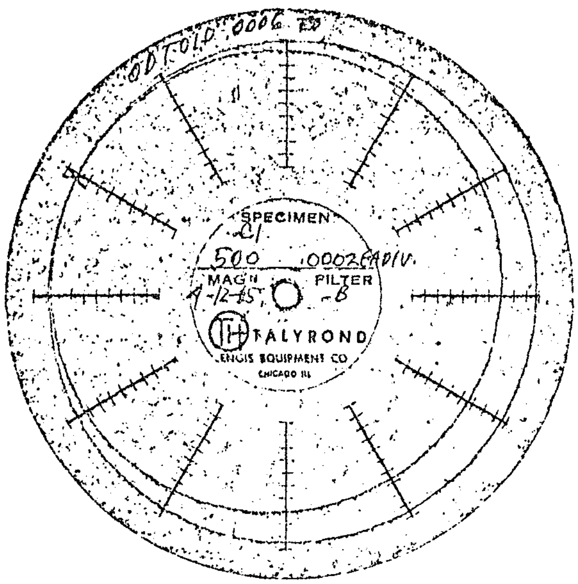


Figure 2-14, Specimen No. C-1

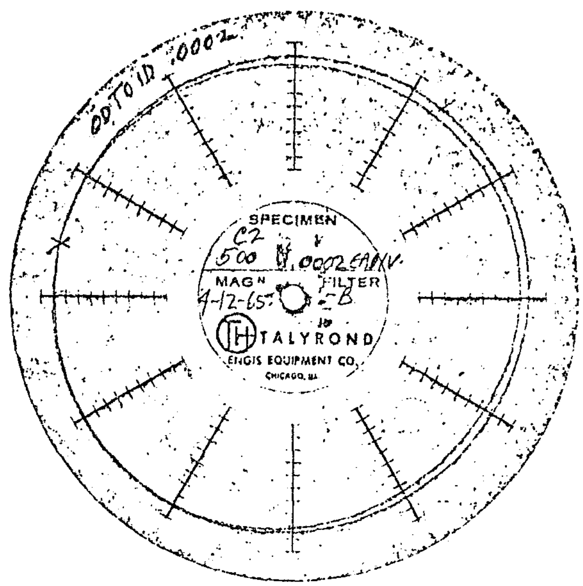


Figure 2-15, Specimen C-2

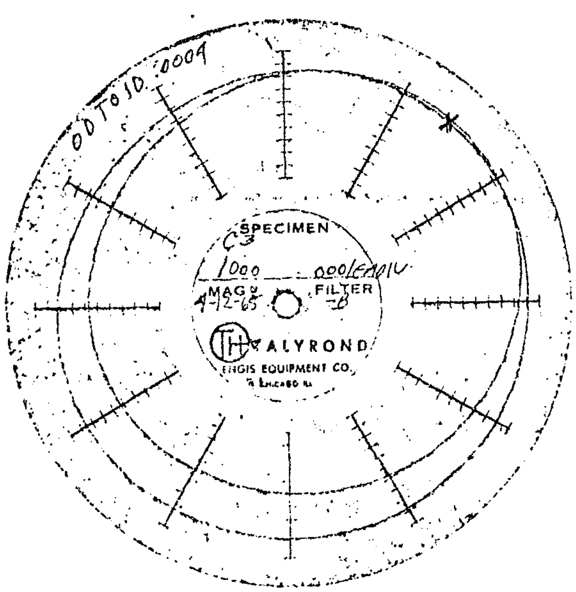


Figure 2-16, Specimen C-3

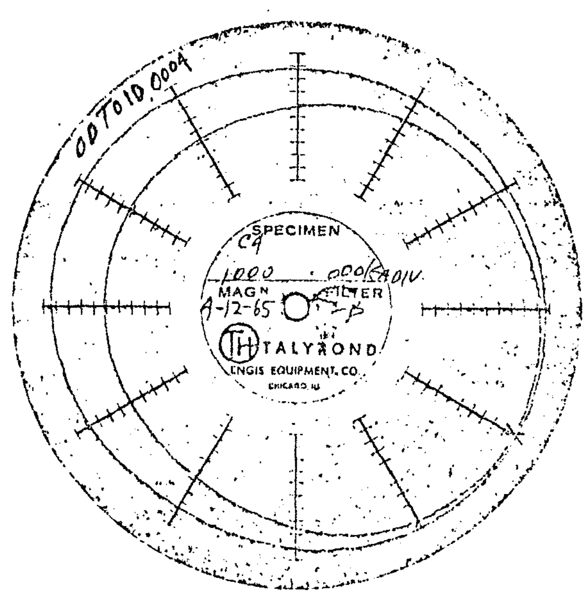


Figure 2-17, Specimen No. C-4

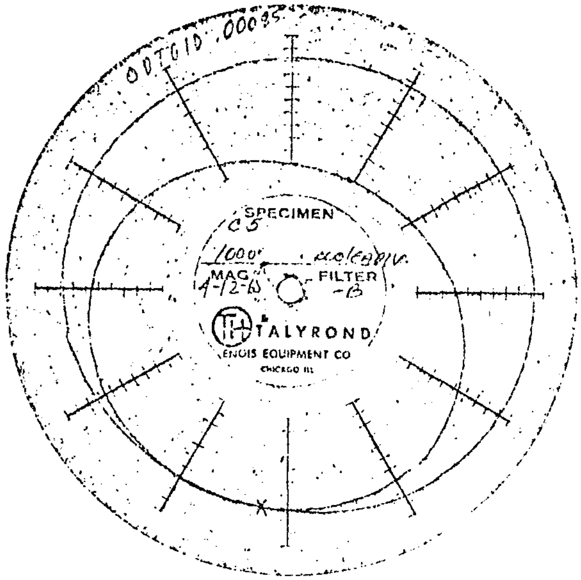


Figure 2-18, Specimen No. C-5

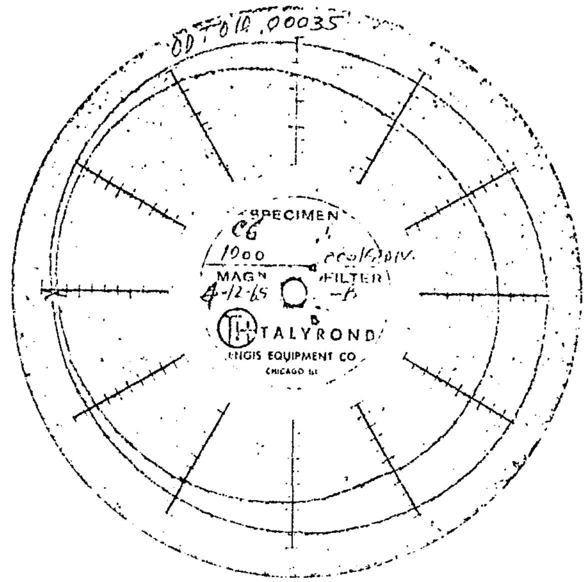


Figure 2-19, Specimen No. C-6

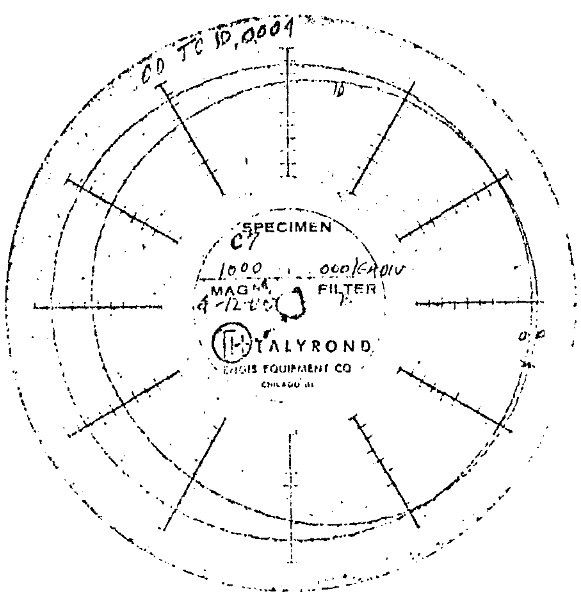


Figure 2-20, Specimen No. C-7

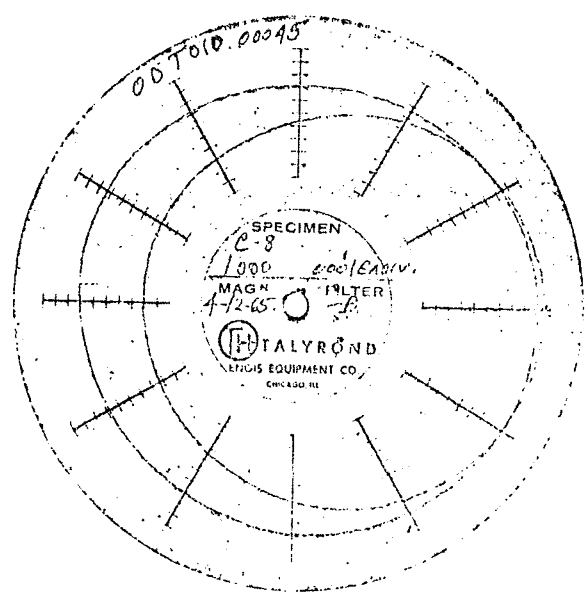


Figure 2-21, Specimen No. C-8

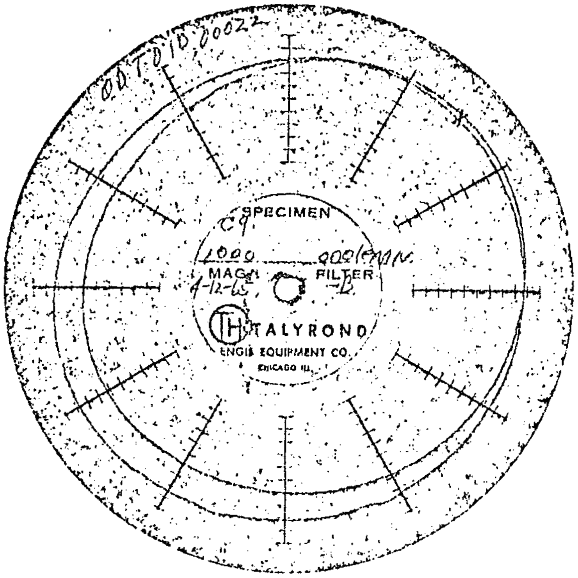


Figure 2-22, Specimen No. C-9

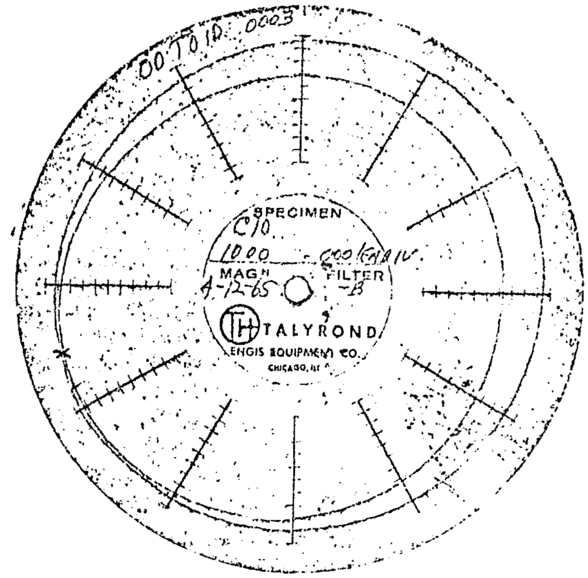


Figure 2-23, Specimen No. C-10

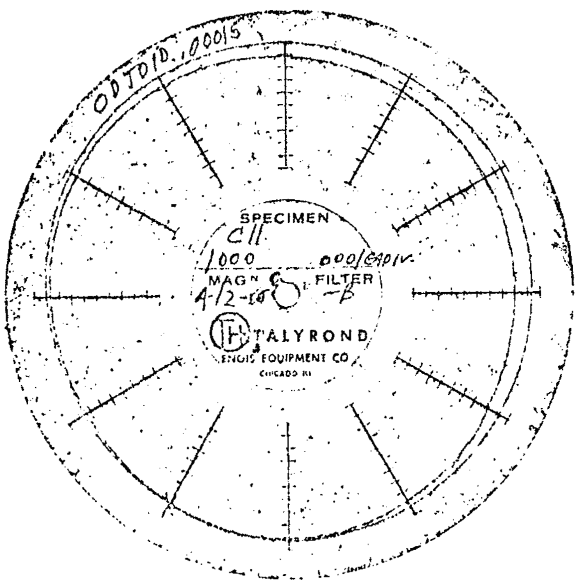


Figure 2-24, Specimen No. C-11

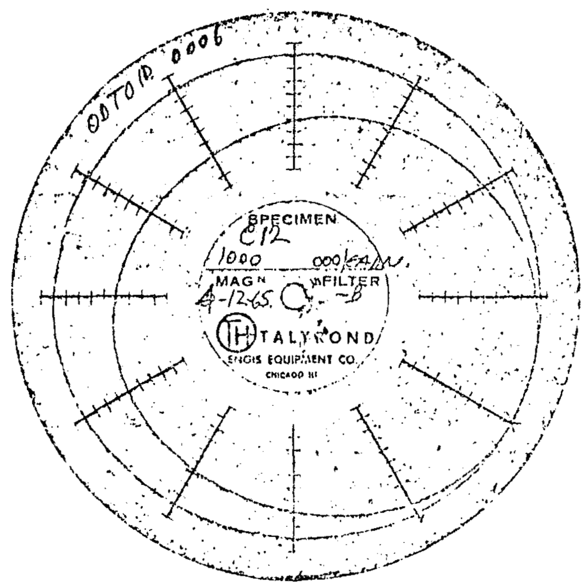


Figure 2-25, Specimen No. C-12

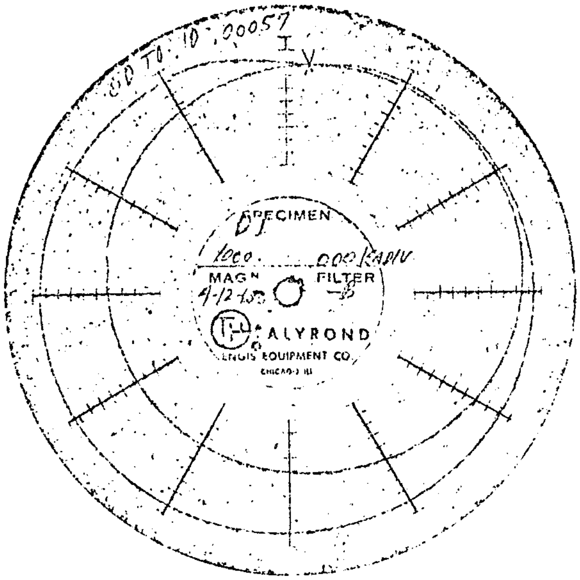


Figure 2-26, Specimen No. D-1

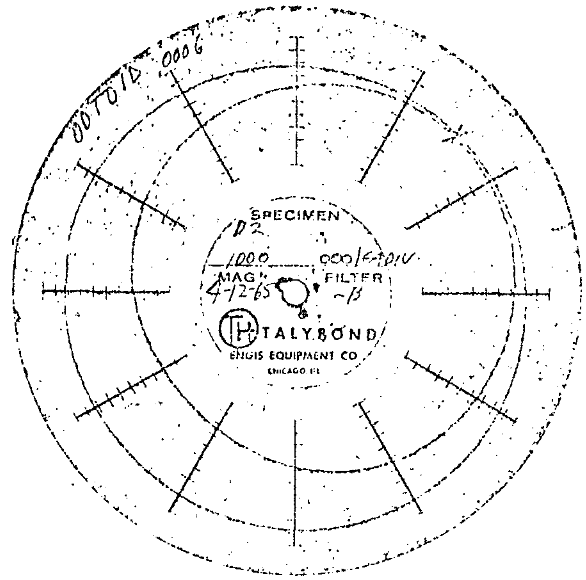


Figure 2-27, Specimen No. D-2

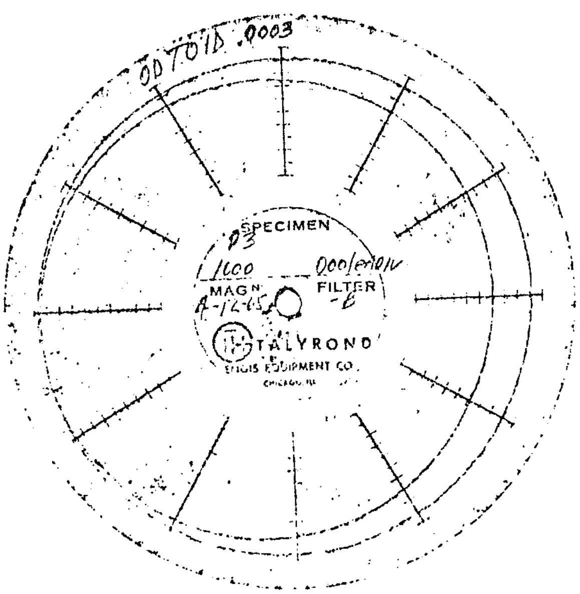


Figure 2-28, Specimen No. D-3

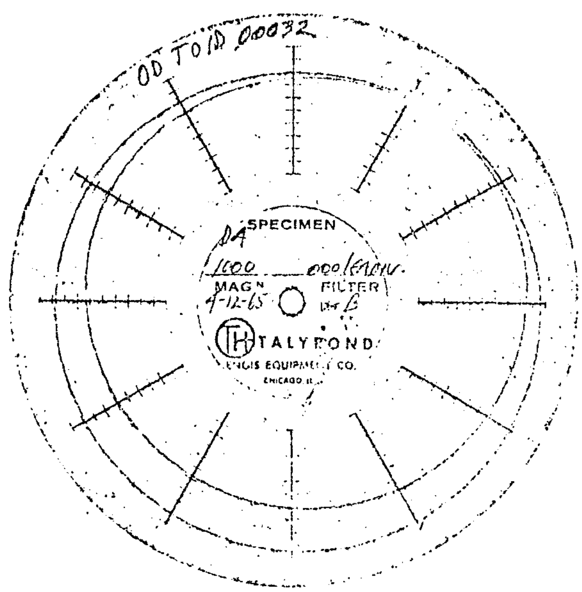


Figure 2-29, Specimen No. D-4

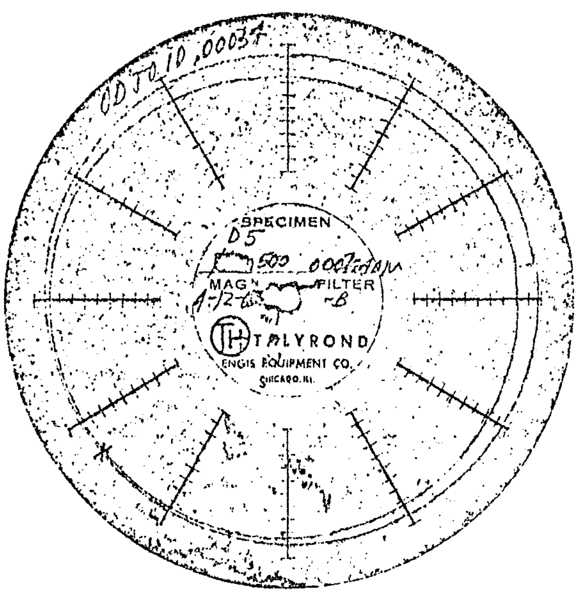


Figure 2-30, Specimen No. D-5

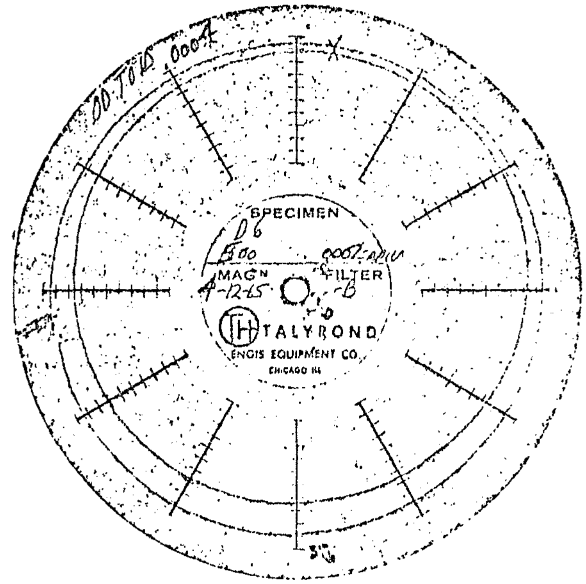


Figure 2-31, Specimen No. D-6

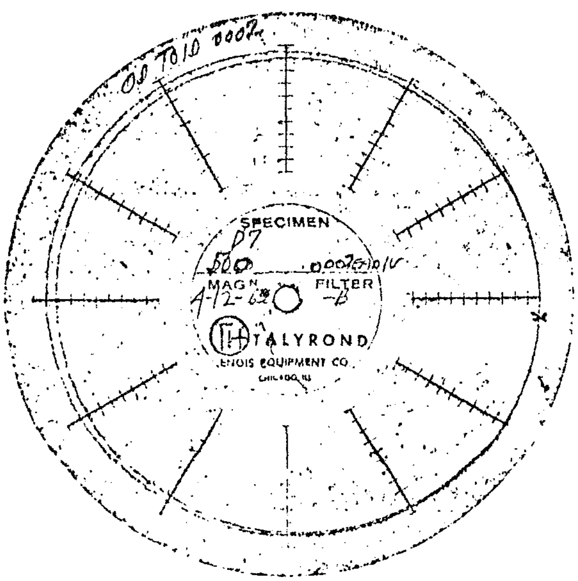


Figure 2-32, Specimen No. D-7

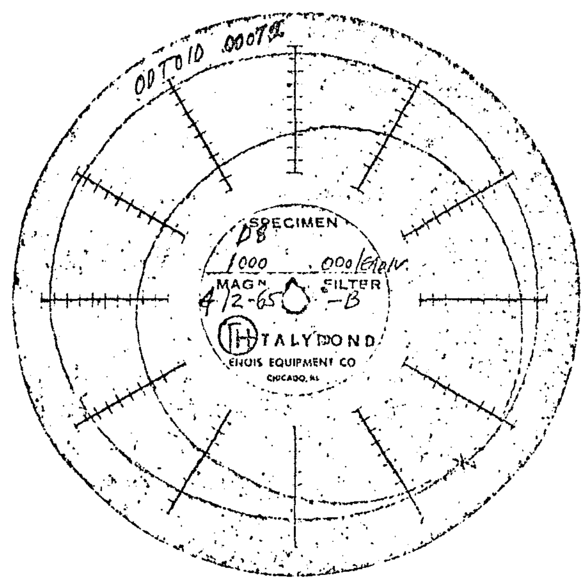


Figure 2-33, Specimen No. D-8

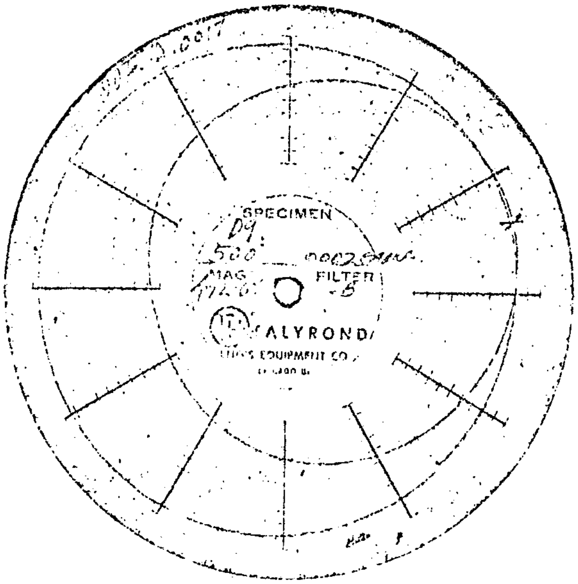


Figure 2-34, Specimen No, D-9

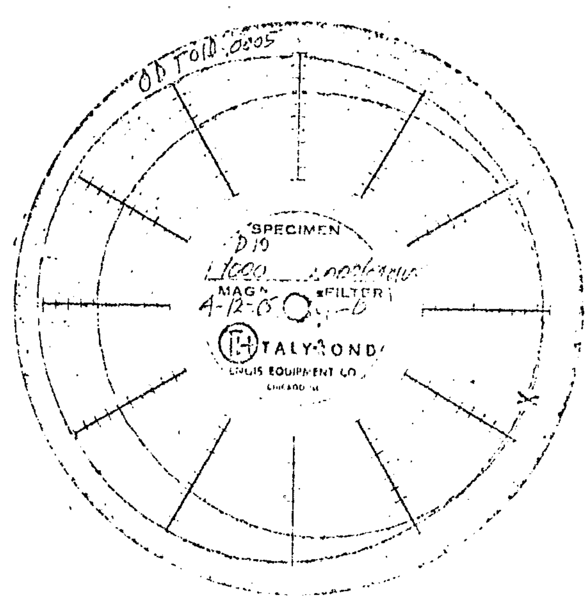


Figure 2-35, Specimen No. D-10

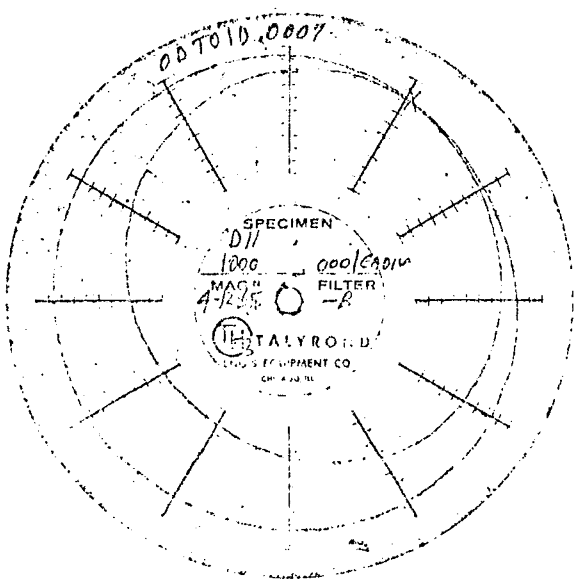


Figure 2-36, Specimen No. D-11

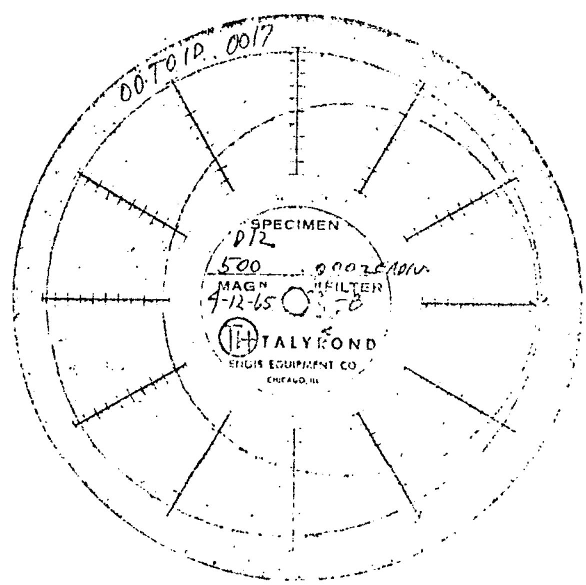


Figure 2-37, Specimen No. D-12

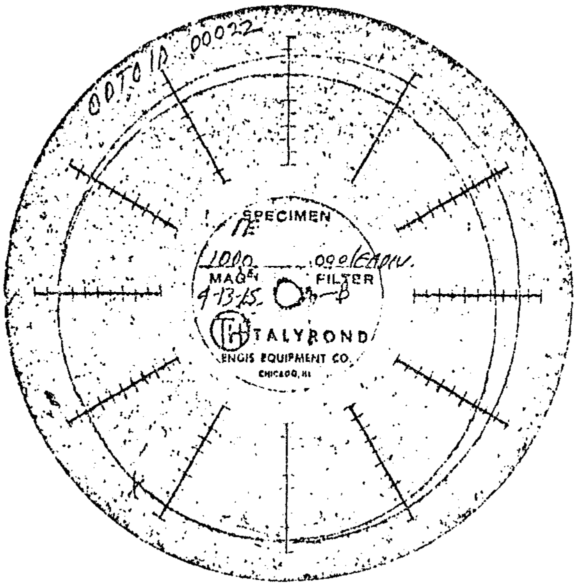


Figure 2-38, Specimen No. E-1

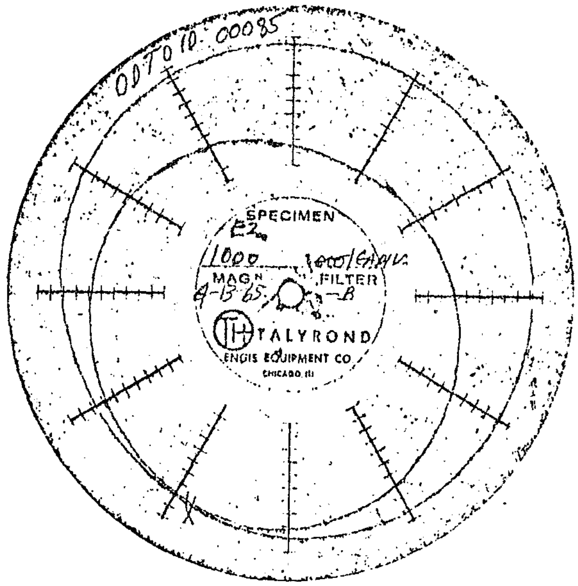
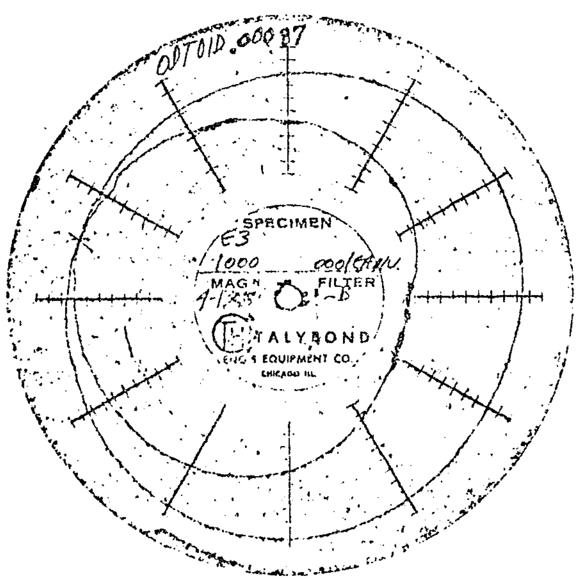


Figure 2-39, Specimen No. E-2



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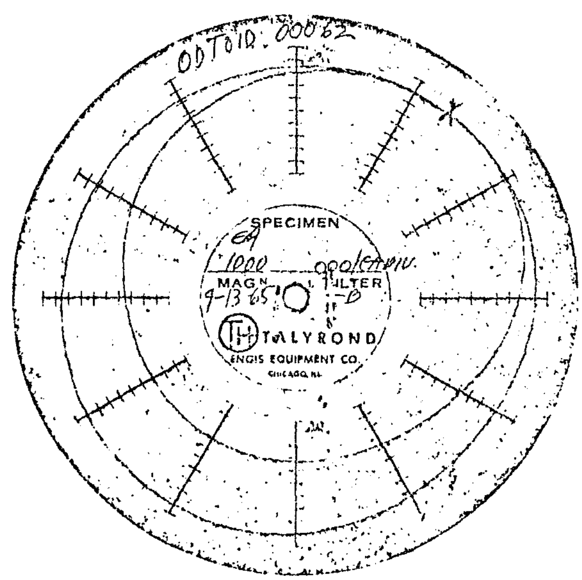

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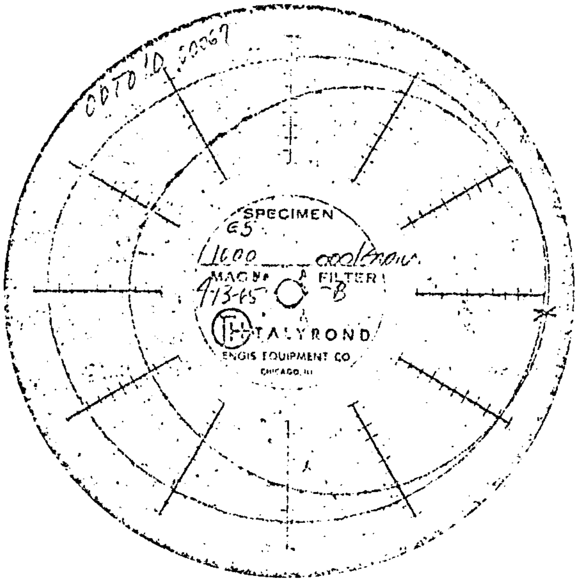

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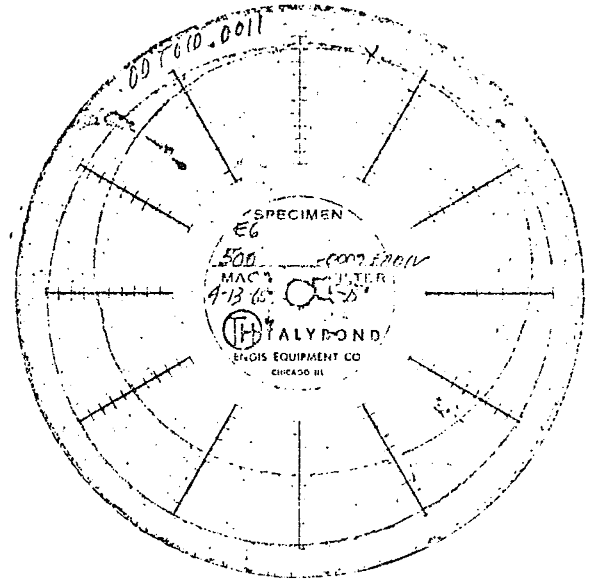

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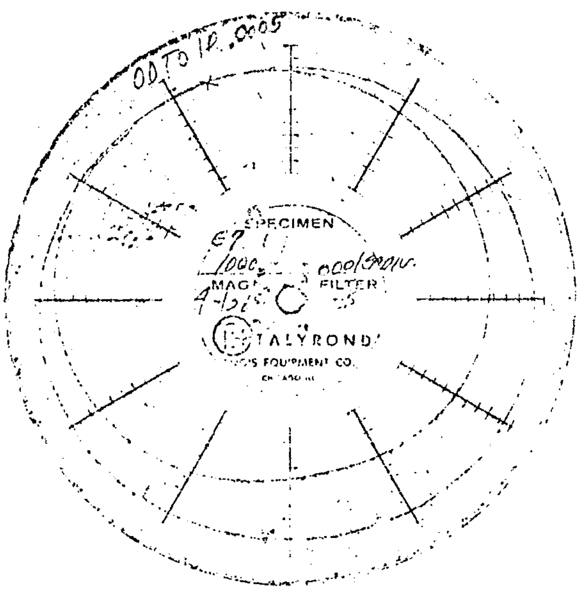

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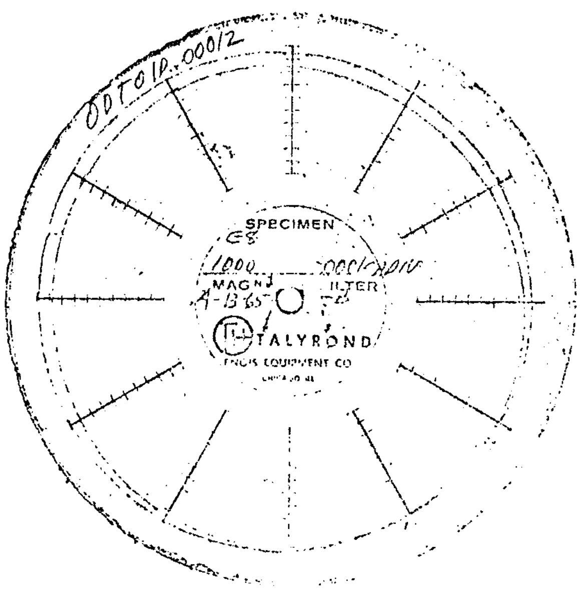


Figure 2-45, Specimen No. E-8

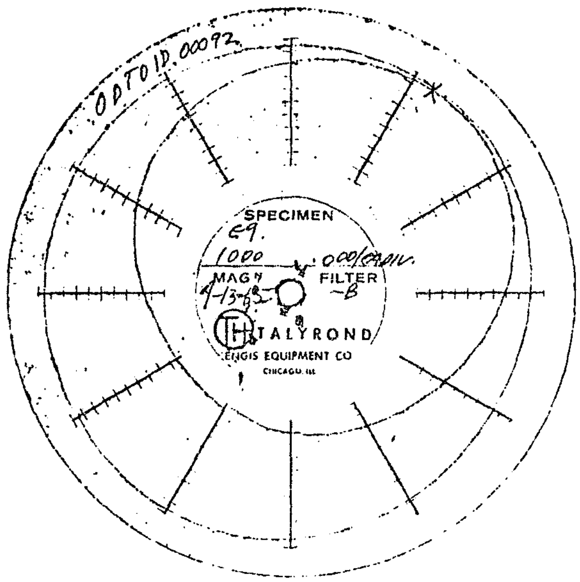


Figure 2-46, Specimen No. E-9

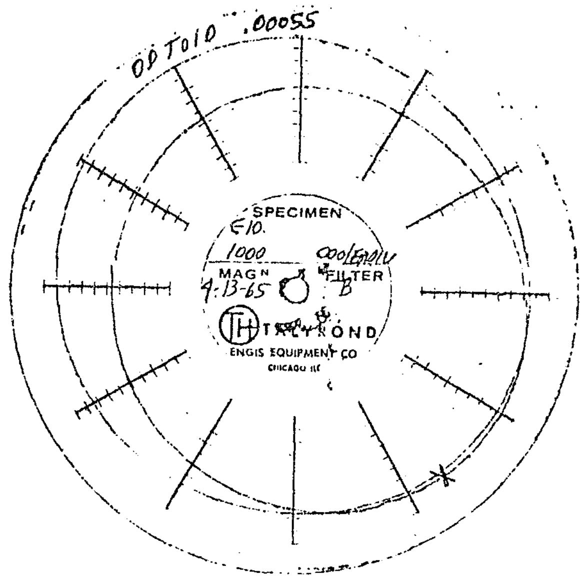


Figure 2-47, Specimen No. E-10

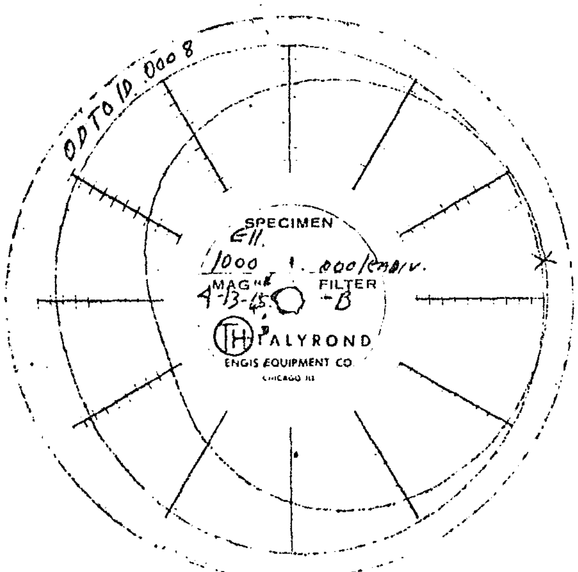


Figure 2-48, Specimen E-11

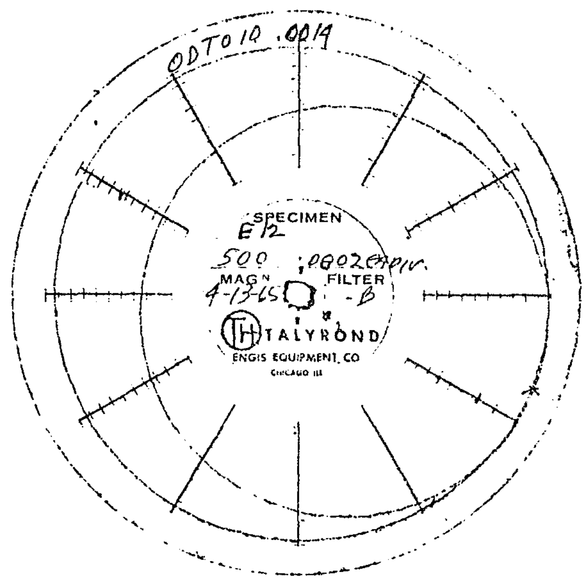


Figure 2-49, Specimen No. E-12

APPENDIX B

METALLOGRAPHIC EXAMINATIONS OF PRESSURIZED TYPE TENSILE SPECIMENS

COPY

MEMORANDUM

TO: Mr. C. E. Cataldo
R-P&VE-MM

FROM: R. F. Manzell
Brown Eng. Co., Inc.
SVD, Materials Dept.

DATE: April 19, 1966

SUBJECT: Hydrogen Embrittlement of A302 Grade B Nickel Modified Steel

Introduction

Specimens of A302 Grade B nickel modified steel that had been subjected to hydrogen embrittlement studies by Brown Engineering Co., Inc., Test Division, Huntsville, Alabama were secured for metallurgical studies by R-P&VE-MM. The specimens had been subjected to sustained tensile stresses at selected levels between 50,000 psi and 130,000 psi in environments of low oxygen content hydrogen, helium, nitrogen and hydraulic oil. The exposure period was for a nominal 24 hours after which the external pressure was gradually increased until the specimens failed. The nominal holding pressure was 6,000 psi; the tensile stress was varied by varying the cross sectional area of the specimen.

Summary

Metallographic examination showed that specimens failed in $H_2(g)$ exhibited secondary cracking in the necked area and also secondary cracking to a much smaller degree in the shank area. No secondary cracking, either in the necked area or in the or in the shank area, was found in specimens failed in $N_2(g)$, He(g) or hydraulic oil. The secondary cracking associated with hydrogen exposure occurs after plastic deformation in localized areas. The micro-crack propagation rate in these localized areas is relatively low.

Procedure

Specimens representative of the various test conditions were selected for metallurgical examination. The attached pictures illustrate many of the following conclusions:

(1) Specimens failed in $H_2(g)$ exhibited secondary cracking in the necked area and also secondary cracking to a much smaller degree in the unreduced shank area.

(2) Specimens exposed and failed in He(g), N_2(g) and hydraulic oil did not exhibit secondary cracking, either in the necked area or in the shank area. The fracture surfaces exhibited typical cup and cone ductile failures.

(3) No correlation was found between the sustained tensile stress and the amount or appearance of secondarycracking associated with specimens tested in H_2(g).

(4) The maximum amount of secondary cracking was found in areas containing a high concentration of inclusions.

(5) Three specimens were removed from test after a 24 hour exposure in H_2(g) at a stress of 120, 000 psi. Both liquid penetrant inspection and metallographic study of these specimens did not reveal any conclusive evidence of secondary cracking. It is concluded that the secondary cracking occurs both in the necked area and the shank area simulataeously with yielding.

(6) One specimen failed after a 36 minute exposure in H_2(g) at a stress level of 120, 000 psi. It was found that this failure occurred in an area containing more than the normal amount of inter-metallics.

(7) Specimens that were fabricated from 4340 steel, Rc 29, and tested in H_2(g) and He(g) were also examined. The results were substantially the same as those found with A302, Gr. B, nickel modified steel. The specimens exposed to He(g) exhibited cup and cone fractures and the specimens exposed to H_2(g) exhibited the same type fracture with secondary cracking both in the necked area and shank area. The 4340 material appeared to be affected more severely by the hydrogen than the A302, Gr. B nickel modified steel.

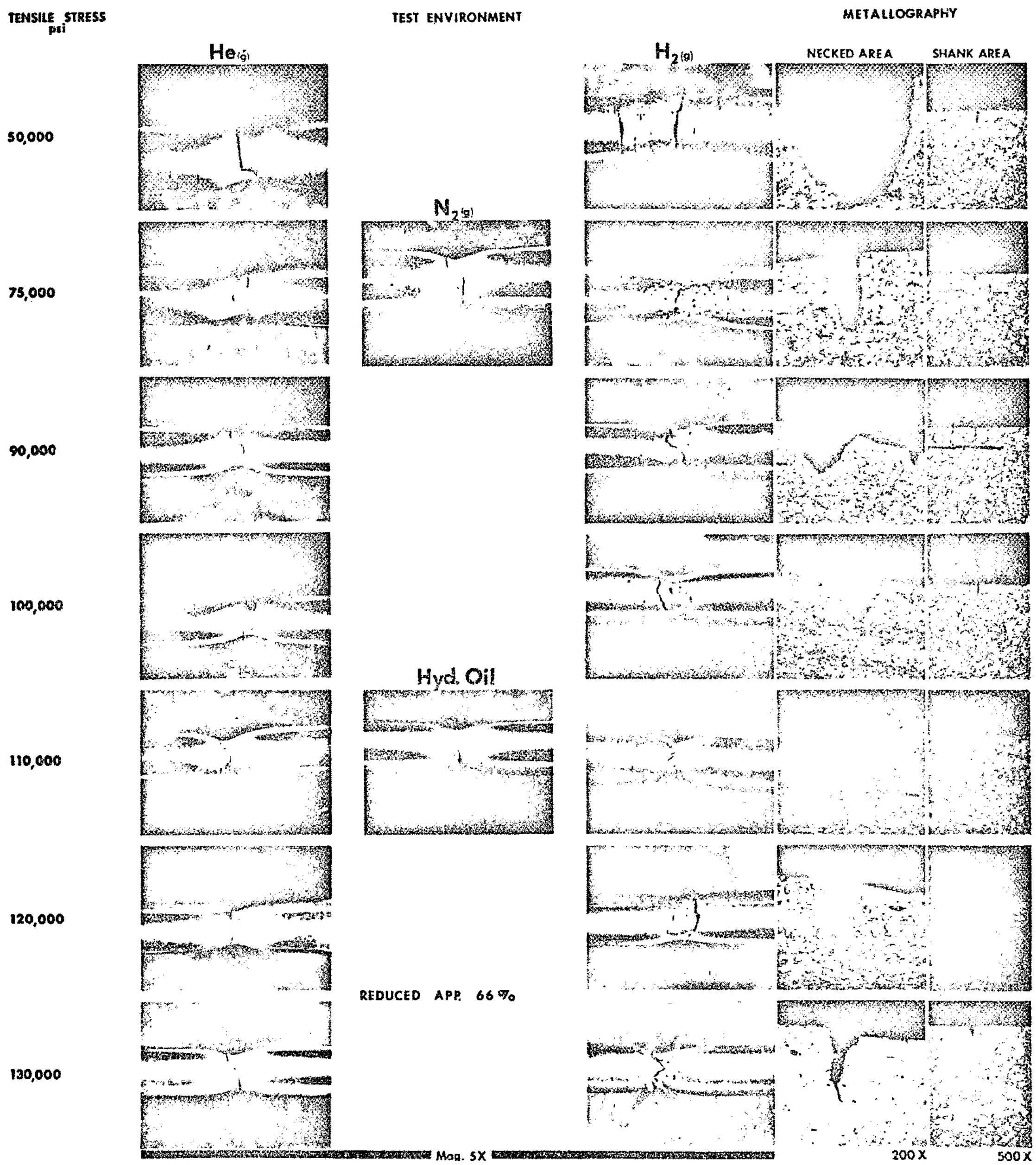
This study is to include the determination of the chemical composition and electron microscope examination of the fracture area. These phases have not been completed.

s/R. F. Manzell

R. F. Manzell
Brown Eng. Co., Inc.
SVD, Materials Dept.

cc: Dr. C. E. Kaylor, SVD
D. R. Morris, SVD
J. Bradley, H. O. D.

HYDROGEN EMBRITTLEMENT TESTS
MATERIAL A-302-56 Gr. B



MEMORANDUM

TO: J. F. X. Weinig, KSC Project Engineer

FROM: J. G. Belcher, Jr. and R. G. Sturm

SUBJECT: Picture Report of H_2 Embrittlement Specimens.

DATE: February 15, 1966

This memorandum presents a pictorial report of the results of hydrogen embrittlement on a representative specimen, X-3-C, and compares the results to a control specimen, X-2-H exposed only to helium. Specimen X-3-C was stored for 25 hours and 27 minutes at 6000 psig with hydrogen at atmospheric temperature. The pressure was then increased to 10,000 psig in 8 minutes and held at 10,000 psig for 5 minutes. The pressure was again increased until the specimen fractured at 10,950 psig. The pressurization time required from 10,000 psig to burst was 2 minutes and 16 seconds. The ultimate tensile strength of specimen X-3-C was calculated to be 129,087 psi.

Figures 1 and 2 show the point of fracture of specimen X-3-C. These photomicrographs were taken 180° apart. Note the irregular shape of the fracture surface. Also note the multiple fracture effect of the specimen surface. The holes indicated by the arrows in Figure 1 are parallel to the machining marks on the surface of the specimen. These machining marks give the hydrogen a point of attack. Similar holes are also shown in Figure 2. Such multiple fractures indicate hydrogen embrittlement.

In a ductile tensile specimen, the point of fracture reduces in area or "necks down." Note that "necking down" in Figures 1 and 2 is very slight. This also indicates that hydrogen embrittlement is present.

Figure 3 shows an enlargement of one of the surface holes pointed out in Figure 1. It may be noted that at the surface hole the material separated without obvious plastic strain but on both ends of the hole evidence of large plastic deformation is present. Such behavior indicates a localized hydrogen embrittlement attack. If the hole was compressed together in an exact axial direction, the ends of the surface scratch (see arrows) would exactly line up. This hole was located very close to the fracture line of the specimen which indicates that it had occurred prior to complete fracture.

Figures 4 and 5 show the inside surface of one of the holes (see footnote 1, Figure 1) as shown enlarged in Figure 3. The photomicrographs in Figures 4 and 5 were taken at the fracture surface of the specimen.

Figure 4 shows three (3) distinct types of fracture. Arrow number 1 points out cleavage fracture typical of embrittled materials. Arrow number 2 points out ductile tear which would normally occur at the center of a ductile tensile specimen. Arrow number 3 points out intergranular fracture typical of hydrogen embrittlement. Figure 5 is a continuation of the surface indicated by arrow number 3 in Figure 4.

Figure 6 shows the "necking down" of helium control specimen X-2-H. There is no evidence of holes in the surface as in the hydrogen embrittlement specimen shown in Figure 1 and 2. Figure 7 is a photomicrograph of the fracture surface of specimen X-2-H and is typical of ductile fracture. The outer area shows shear and the inner area shows ductile tear. The ultimate tensile strength of specimen X-2-H was calculated to be 121, 500 psi.

Although hydrogen embrittlement was present, it is concluded that specimen X-3-C had been embrittled by hydrogen through only a small percentage of the cross-sectional area. The presence of hydrogen embrittlement drastically reduced the true strength at fracture. Using the final diameter of the specimens, the true fracture strength of the specimen in hydrogen was 179, 600 psi, whereas the true fracture strength of the specimen in helium was 356, 800 psi.

J. G. Belcher, Jr.

J. G. Belcher, Jr.
Failure Analysis Project Engineer
Test Department

R. G. Sturm

R. G. Sturm
Staff Consultant, Materials
Research Laboratories

1. Figures 4 and Figure 5 were taken at this point.

Figure 1. Fracture Point of Specimen X-3-C
(Magnification 8X)

Figure 2. Fracture Area of Specimen X-3-C
(Magnification 8X)

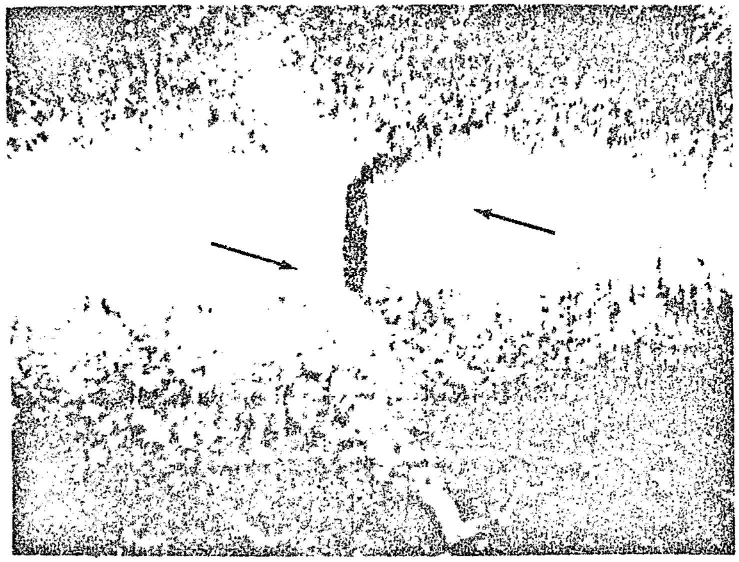


Figure 3. Enlargement of Surface Hole (Magnification 25X)

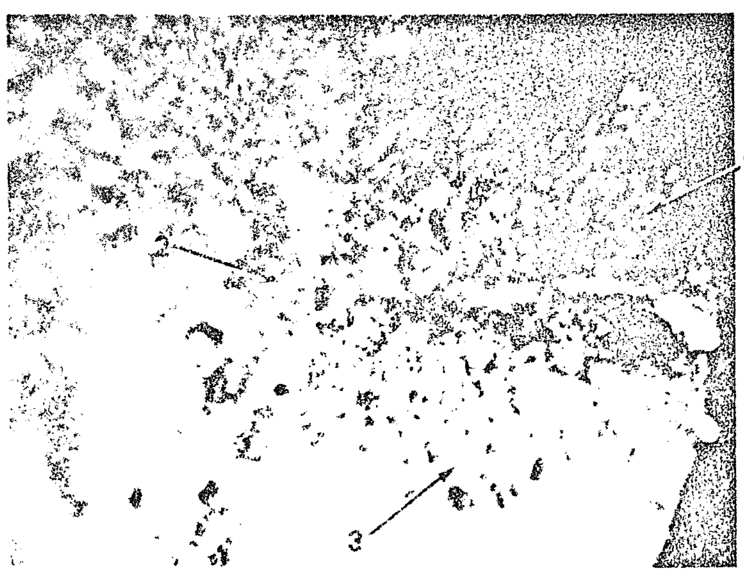


Figure 4. Inside Surface of Hole Taken at Fracture Surface (Magnification 25X)

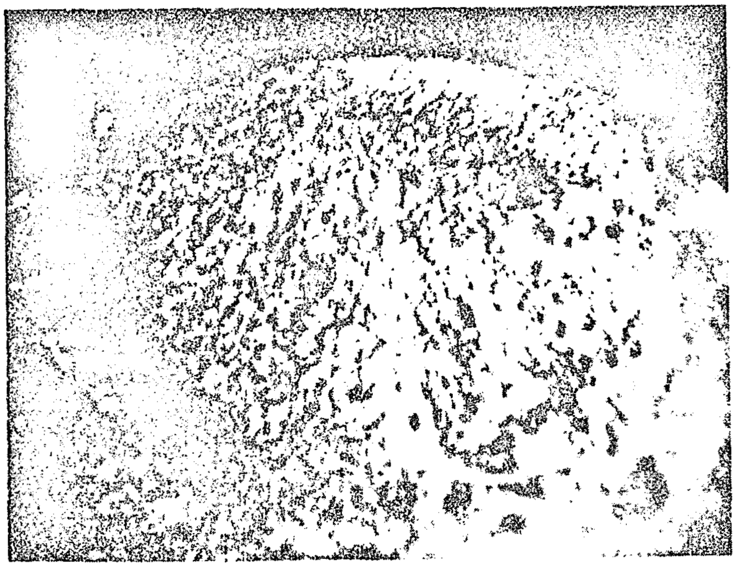


Figure 5. Inside Surface of Hole Showing Intergranular Fracture. (Magnification 25X)

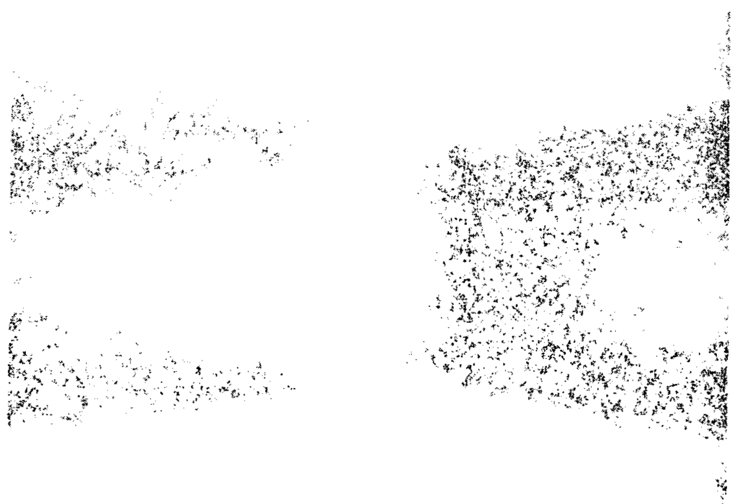


Figure 6. Fracture Point of Helium Control Specimen X-2-II (Magnification 7X)

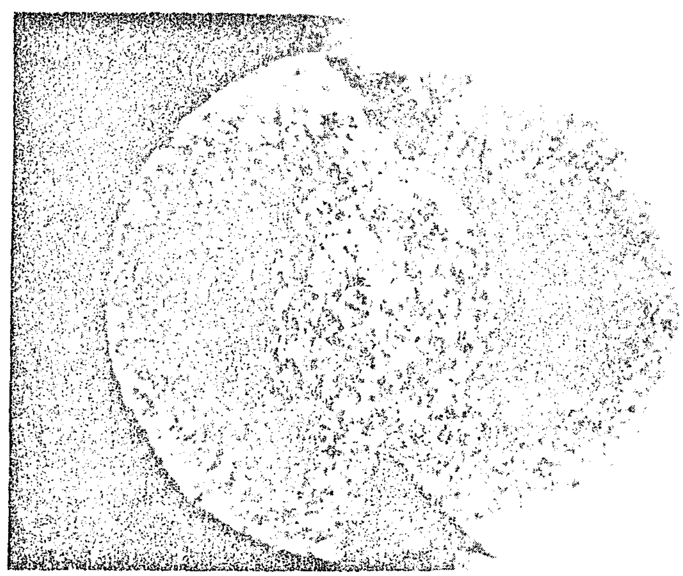


Figure 7. Fracture Surface of Helium Control Specimen X-2-H (Magnification 15X) Specimen Tilted Approximately 30°

APPENDIX C

STRESS VS. STRAIN CURVES FOR TENSILE SPECIMEN TESTS

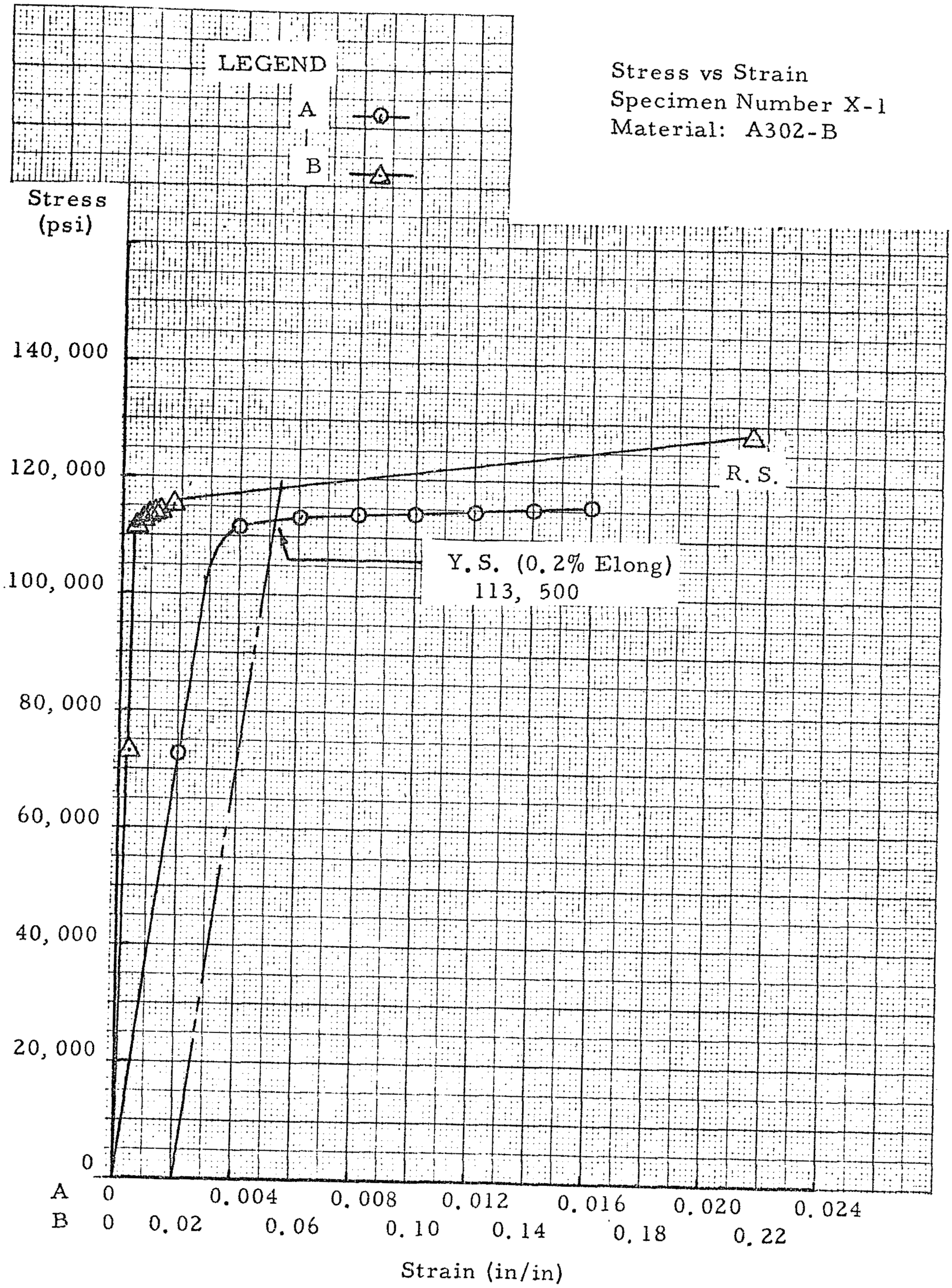


Figure C-1. Stress vs Strain Specimen Number X-1

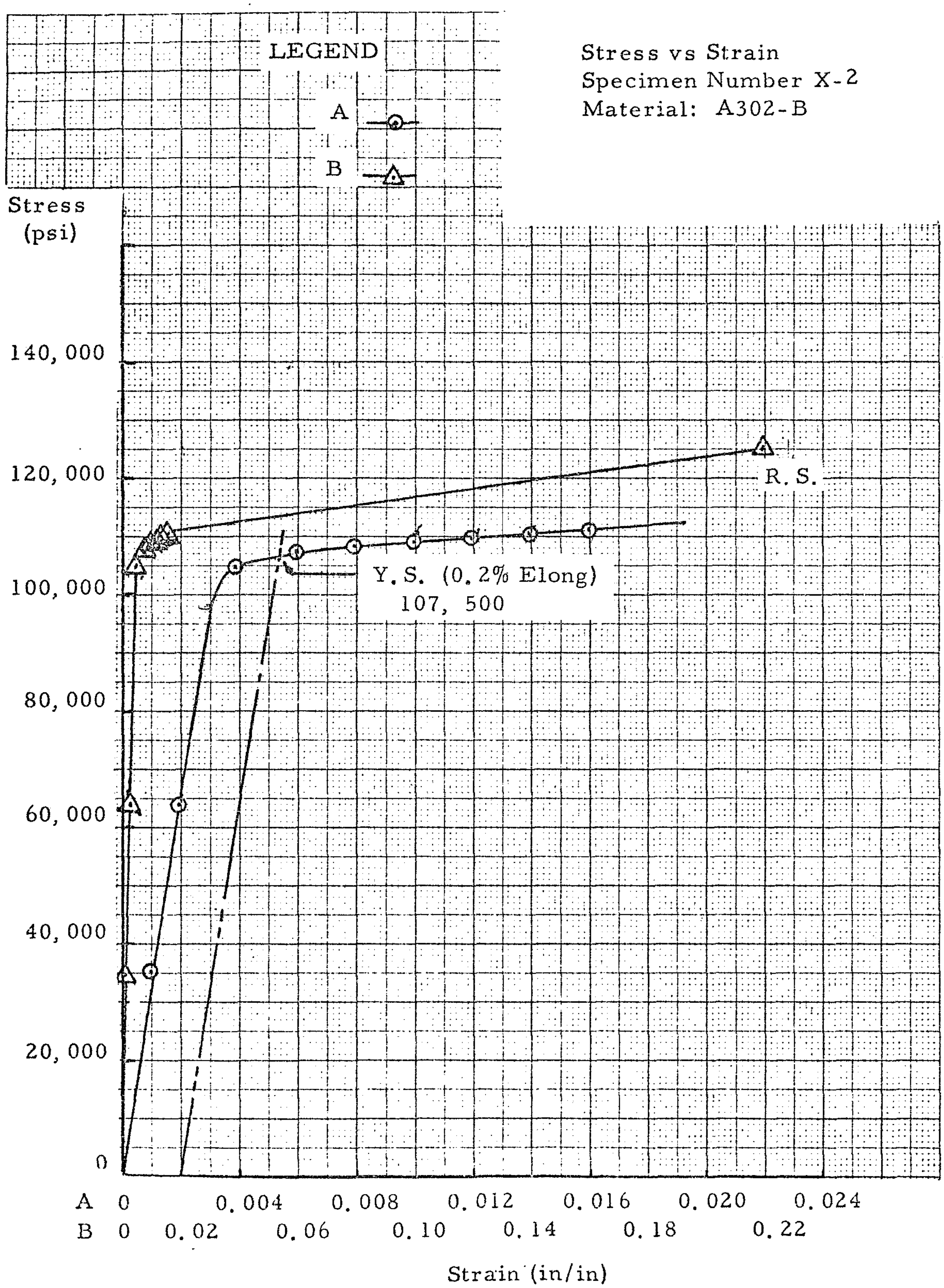


Figure C-2. Stress vs Strain Specimen Number X-2

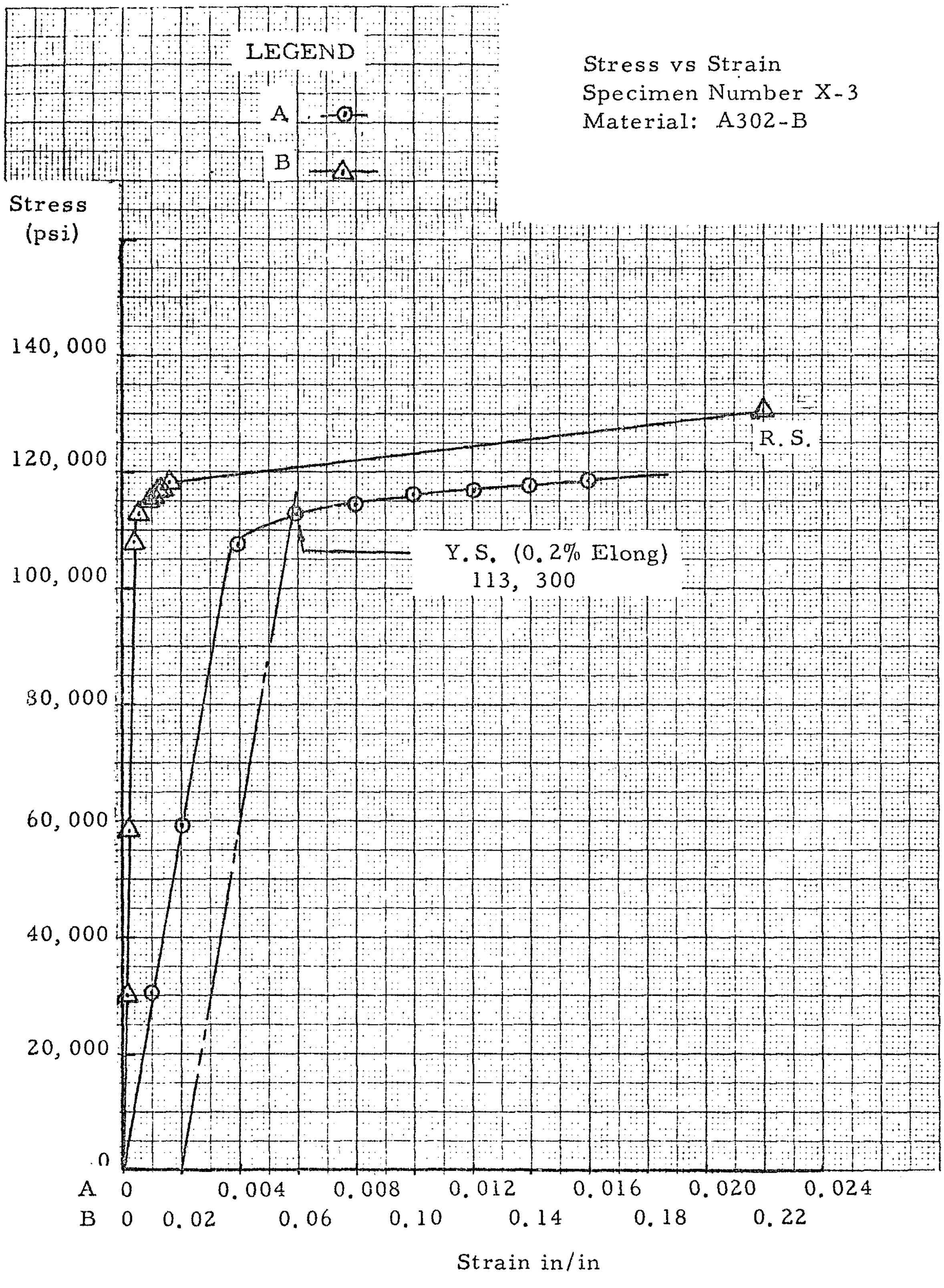


Figure C-3. Stress vs Strain Specimen Number X-3

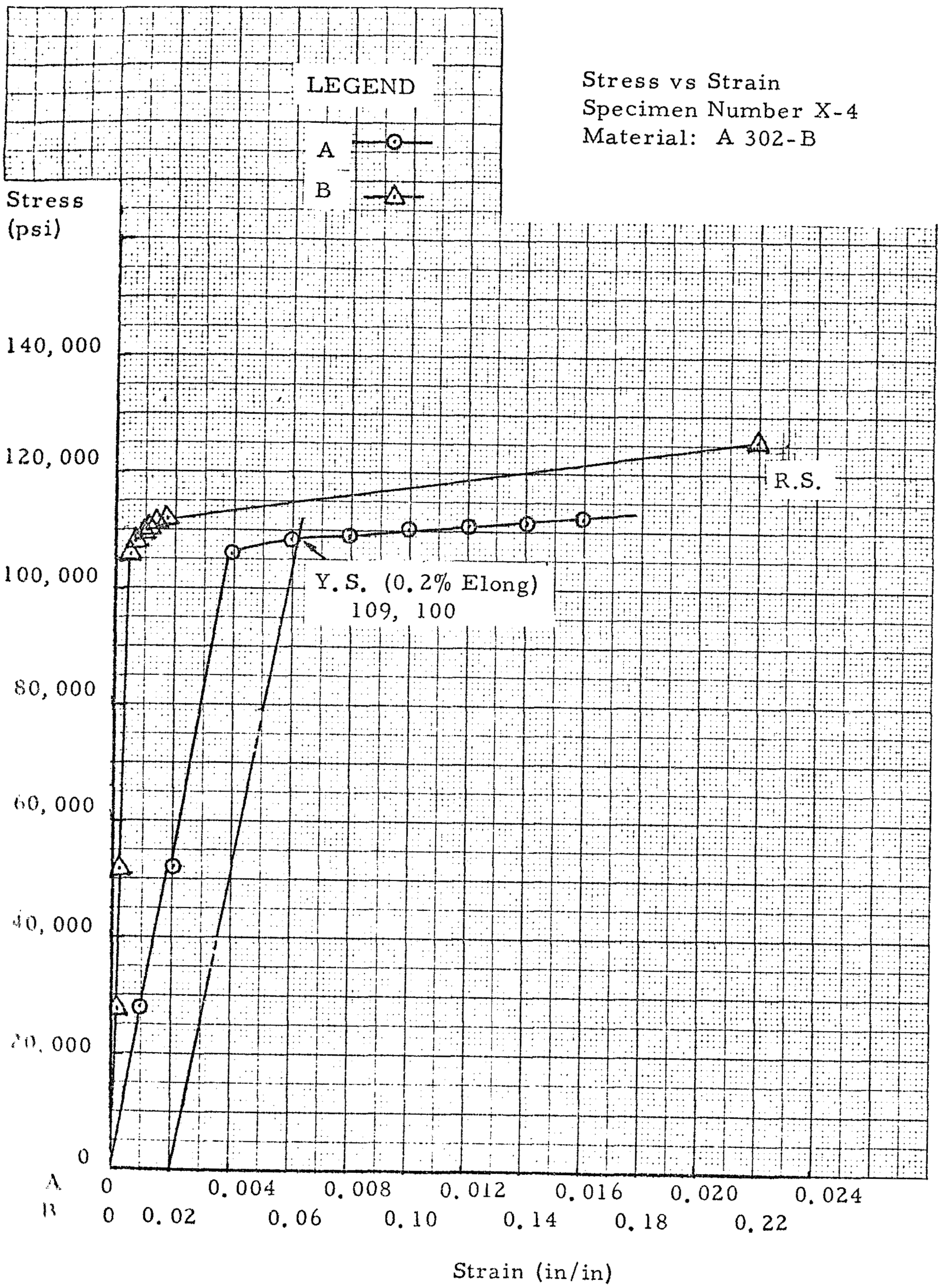


Figure C-4. Stress vs Strain Specimen Number X-4.

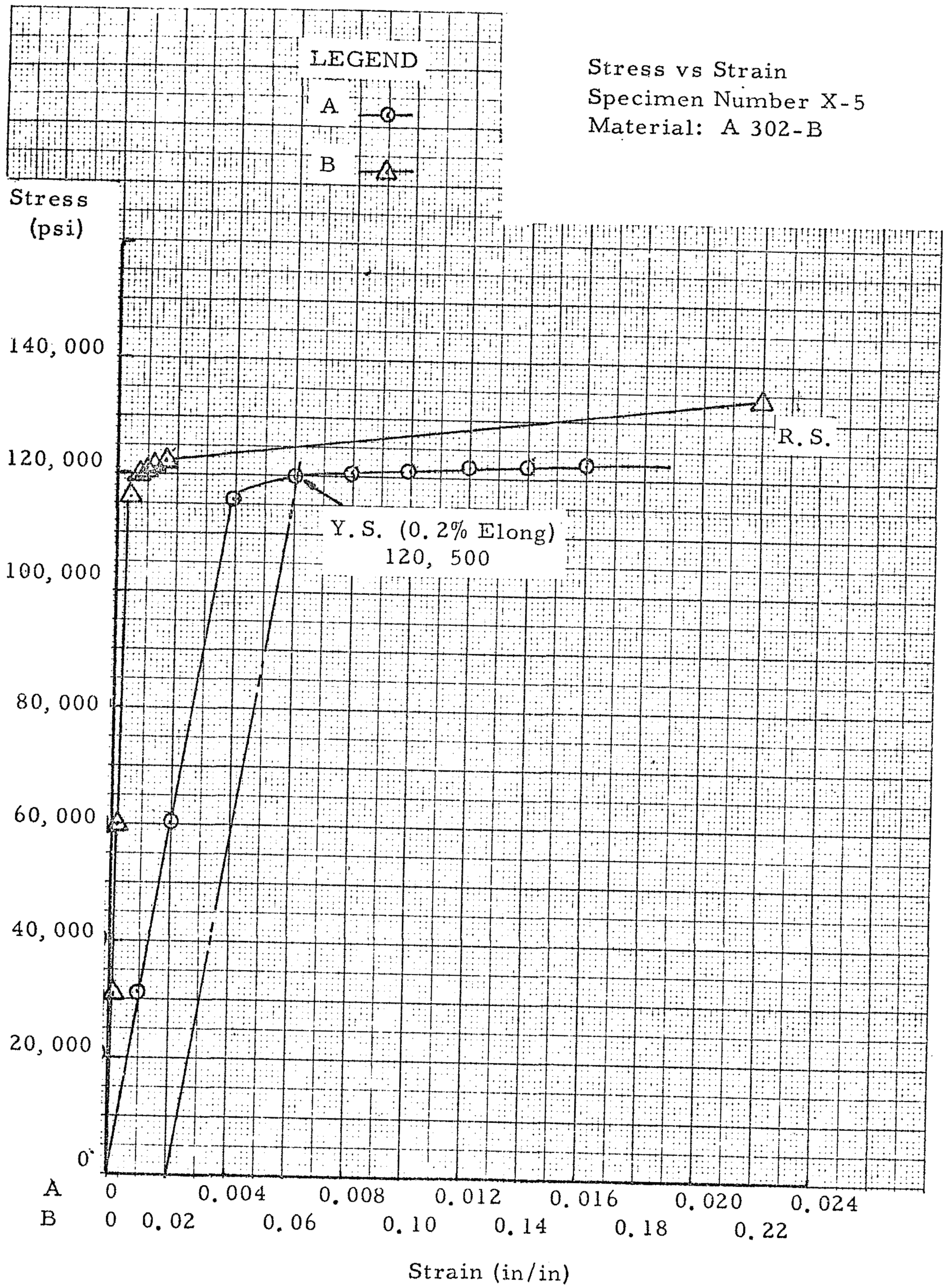


Figure C-5. Stress vs Strain Specimen Number X-5.

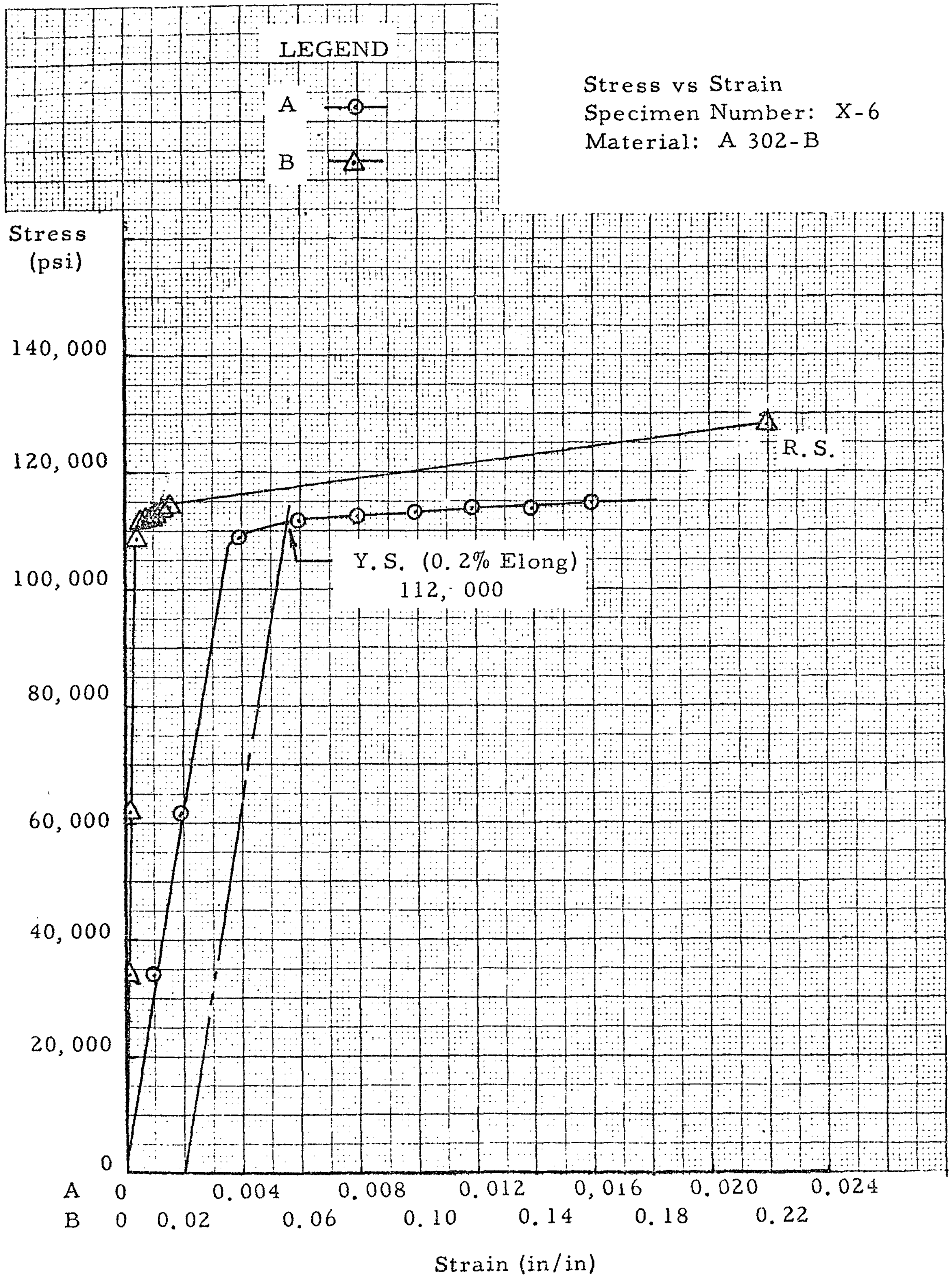


Figure C-6. Stress vs Strain Specimen Number X-6.

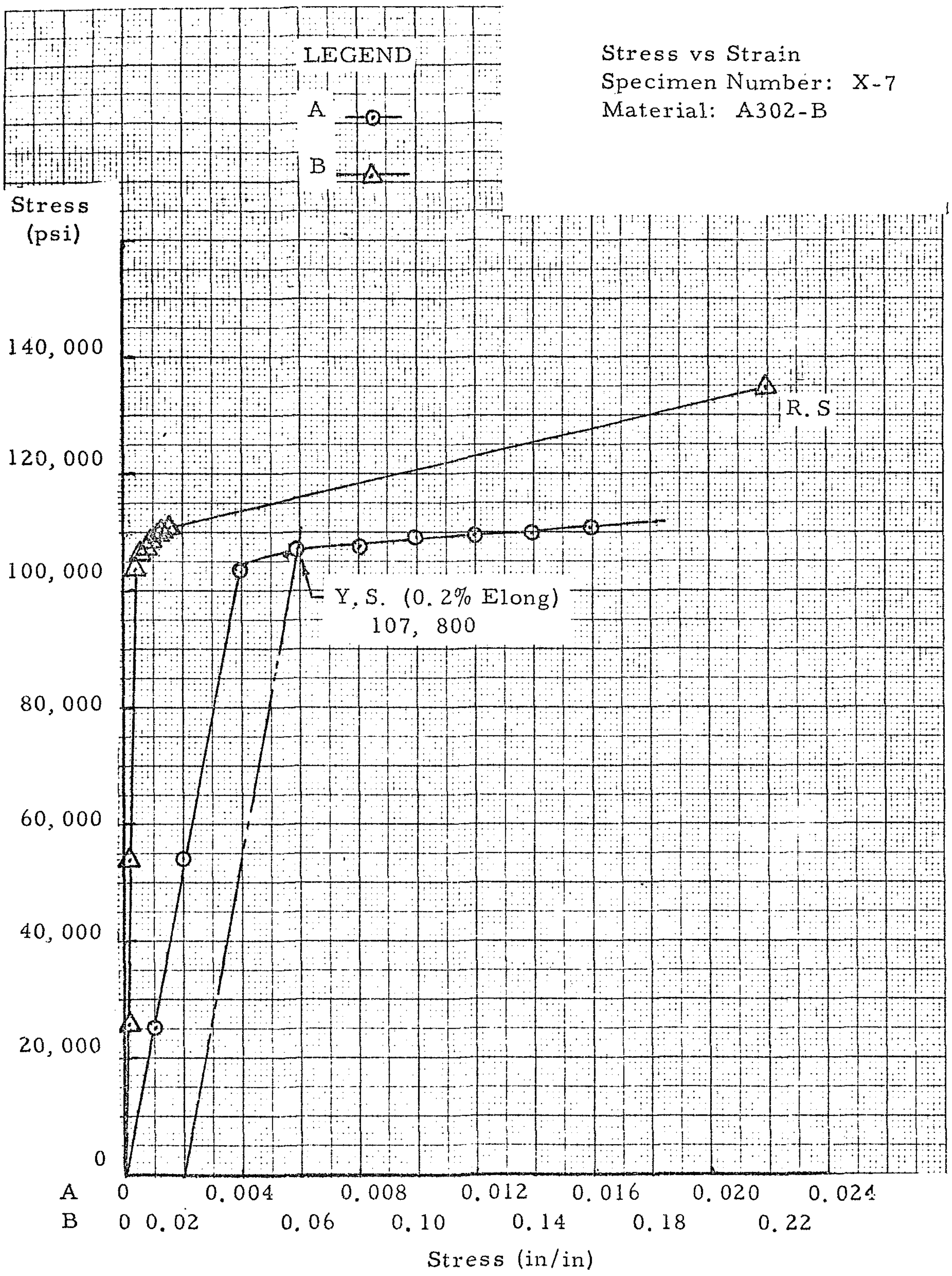


Figure C-7. Stress vs Strain Specimen Number X-7.

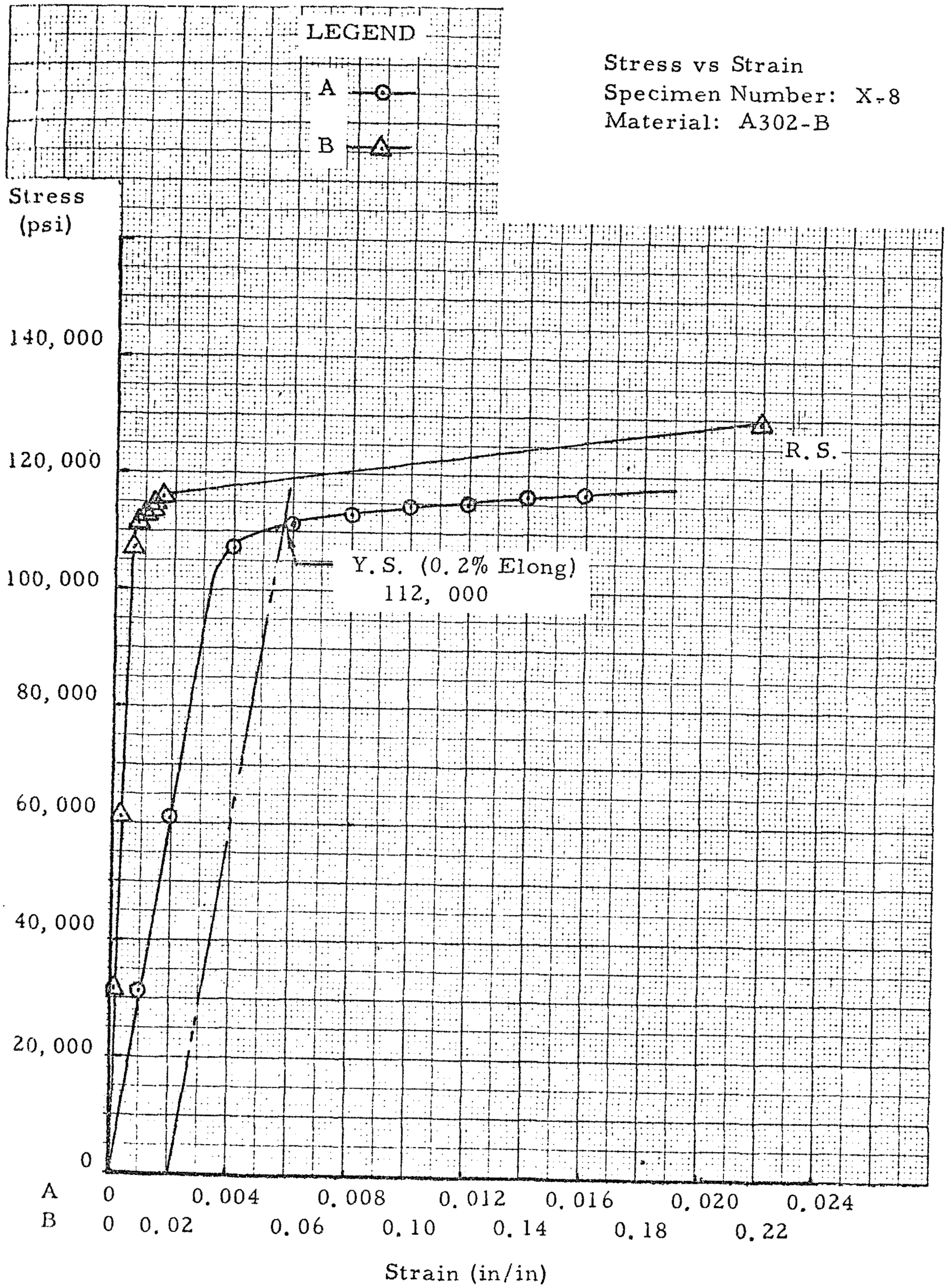


Figure C-8. Stress vs Strain Specimen Number X-8.

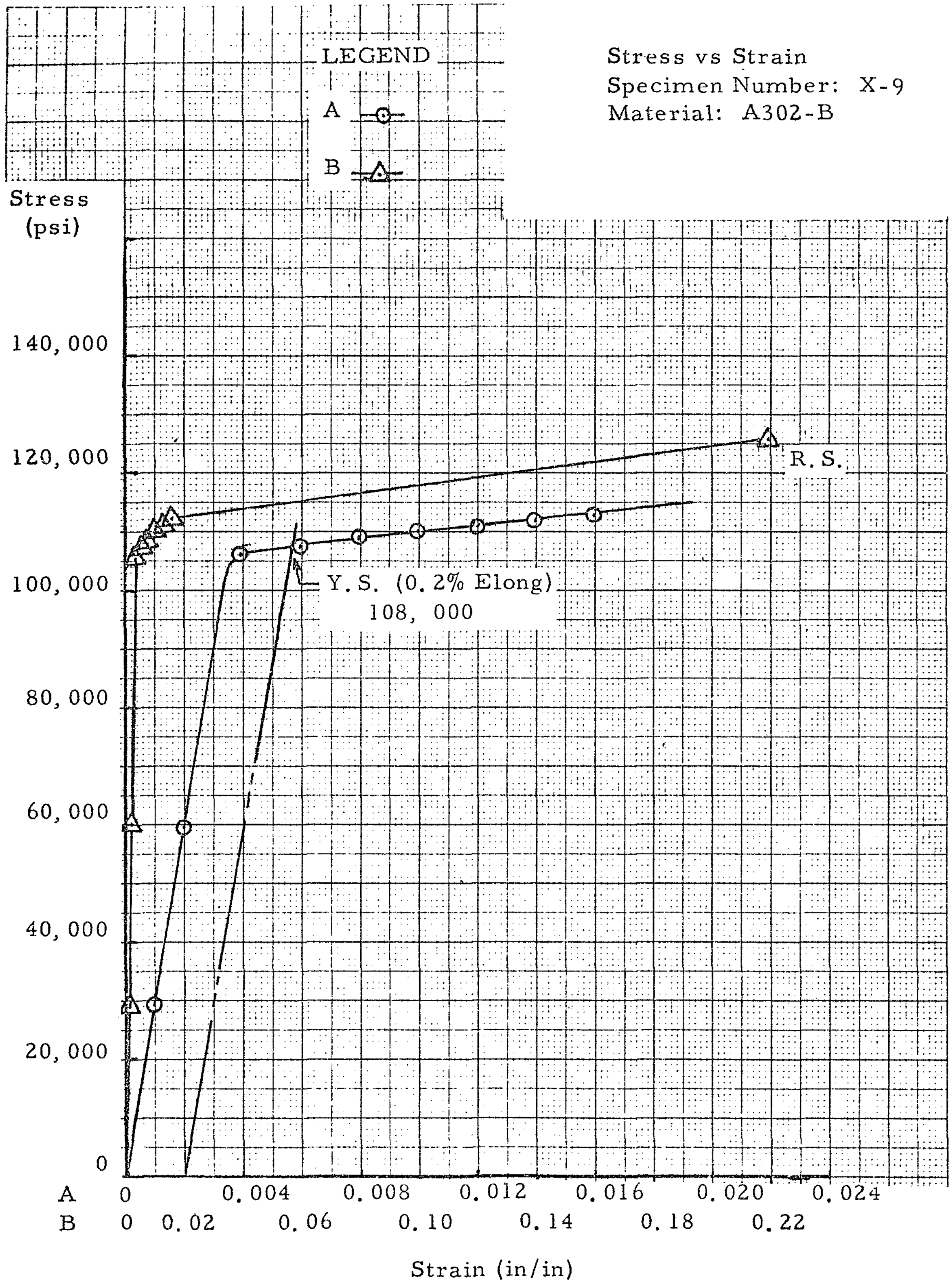


Figure C-9. Stress vs Strain Specimen Number X-9.

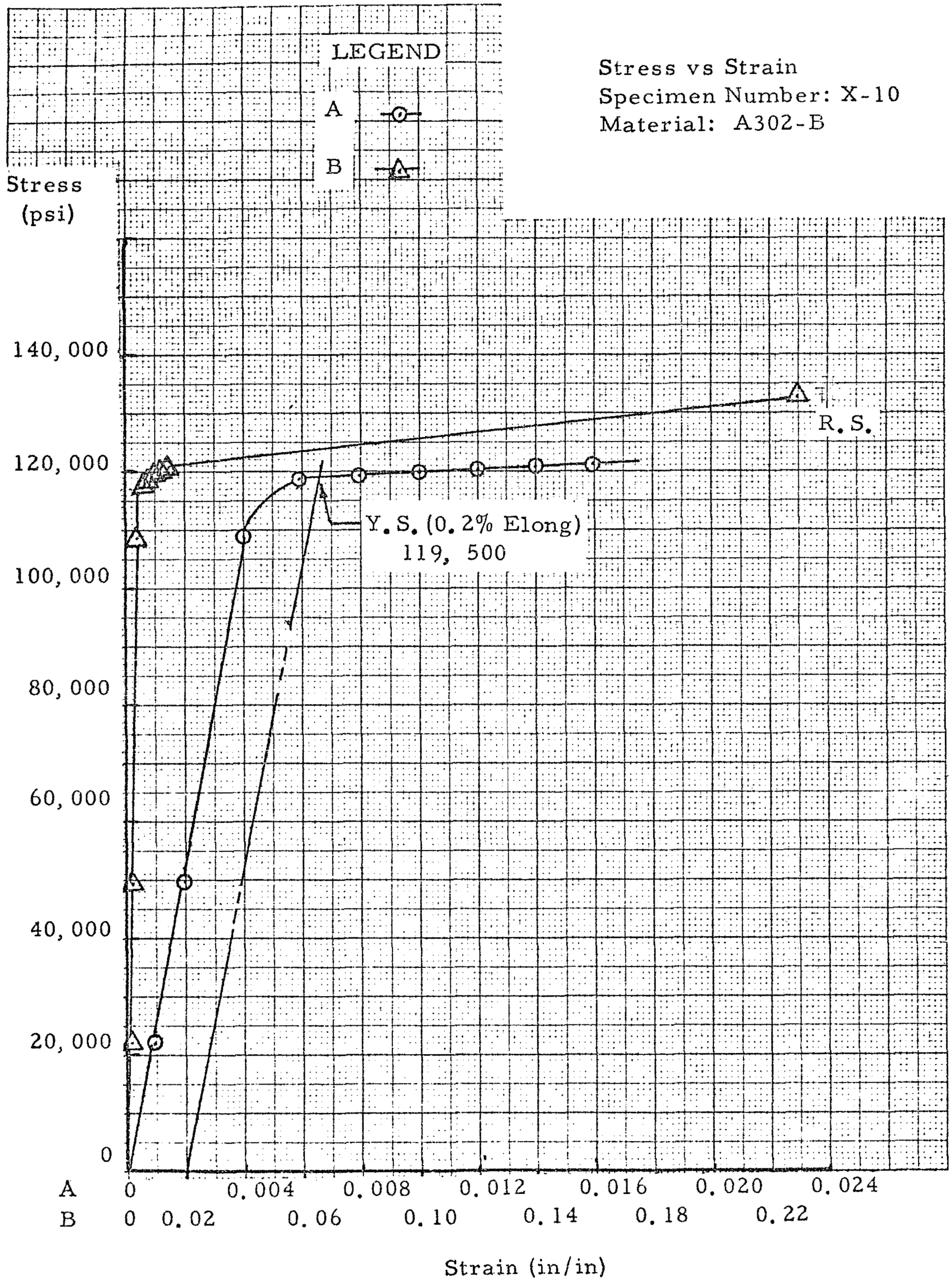


Figure G-10. Stress vs Strain Specimen Number X-10.

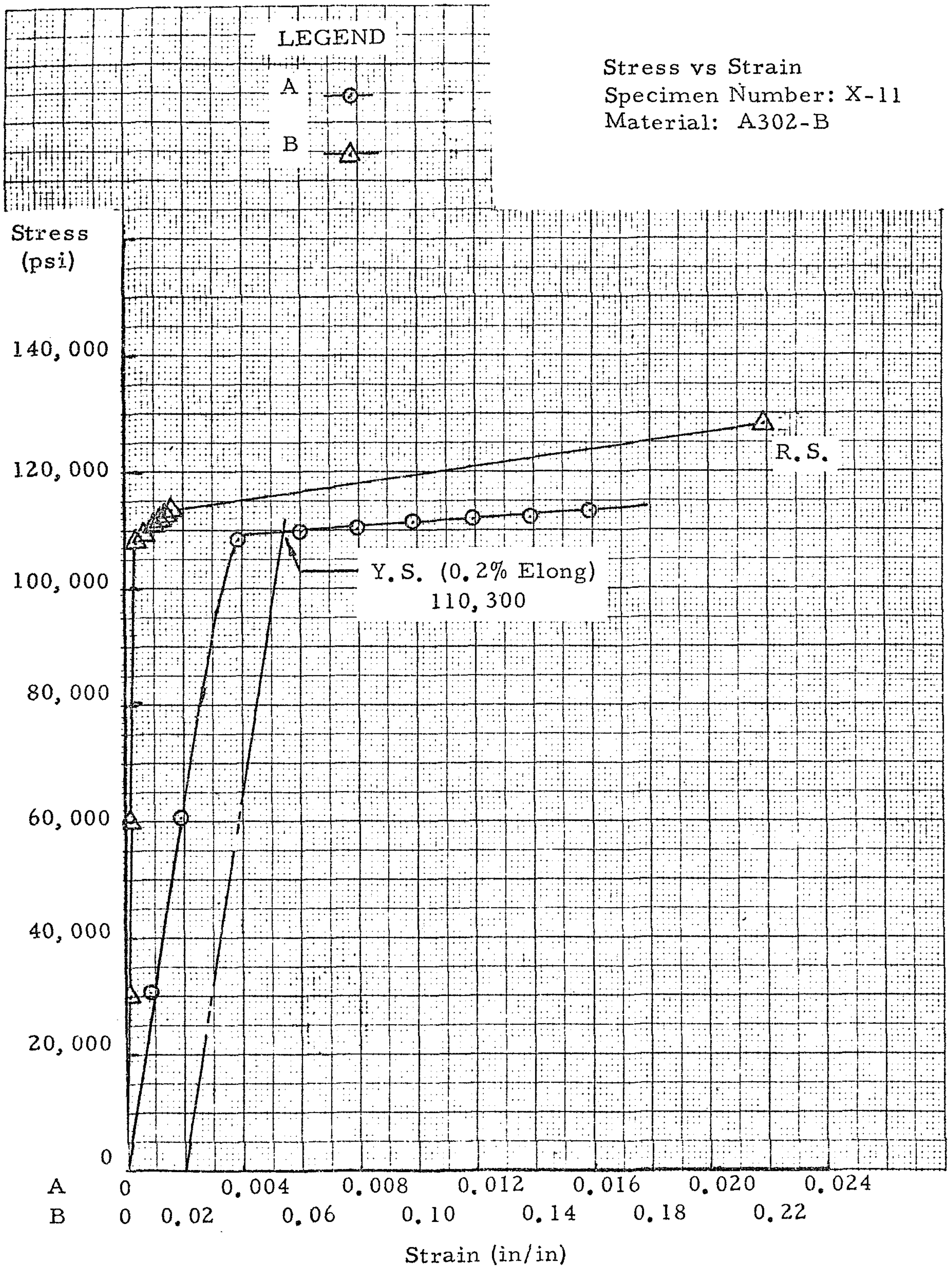


Figure C-11. Stress vs Strain Specimen Number X-11.

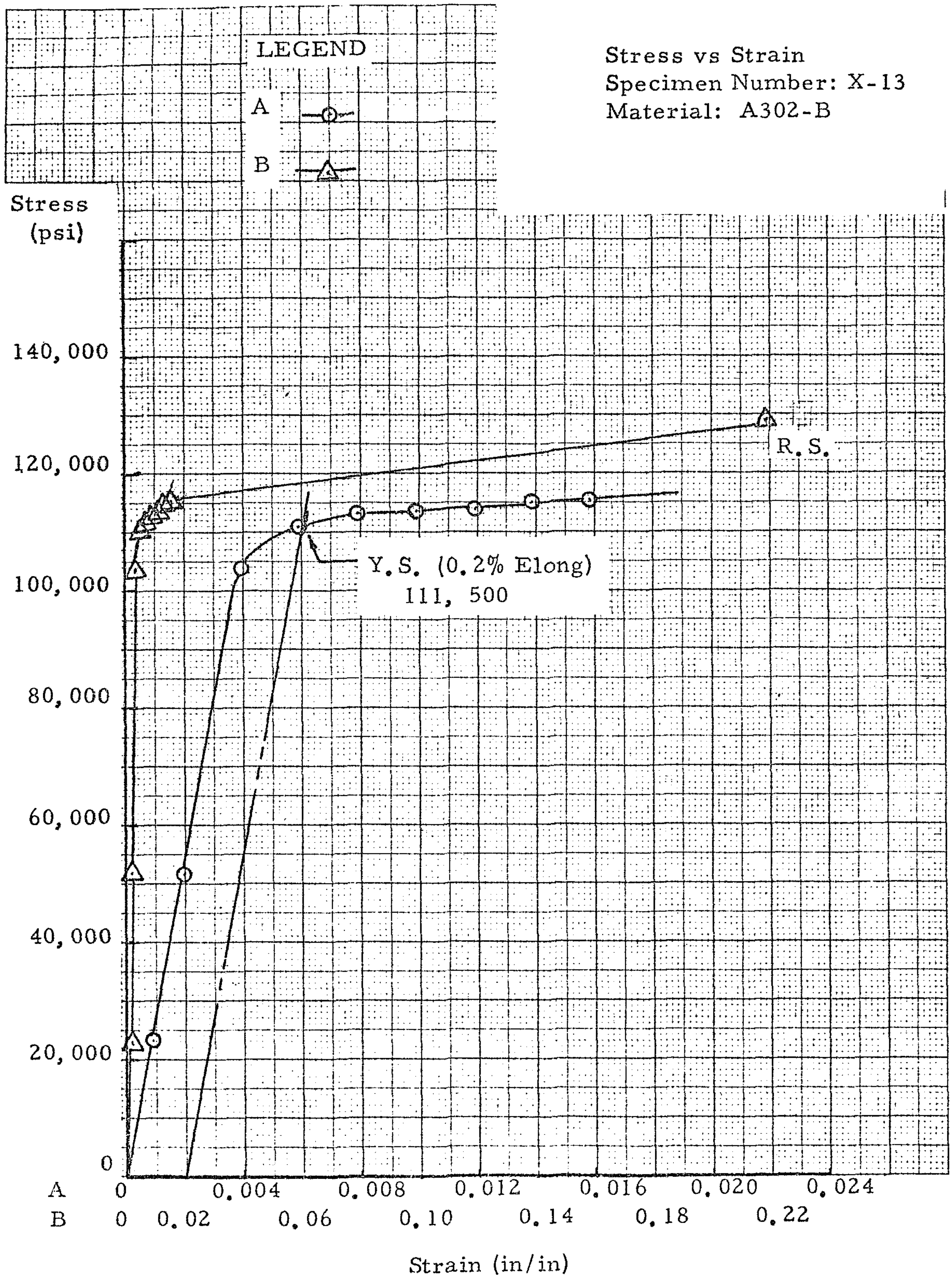


Figure C-12. Stress vs Strain Specimen Number X-13.

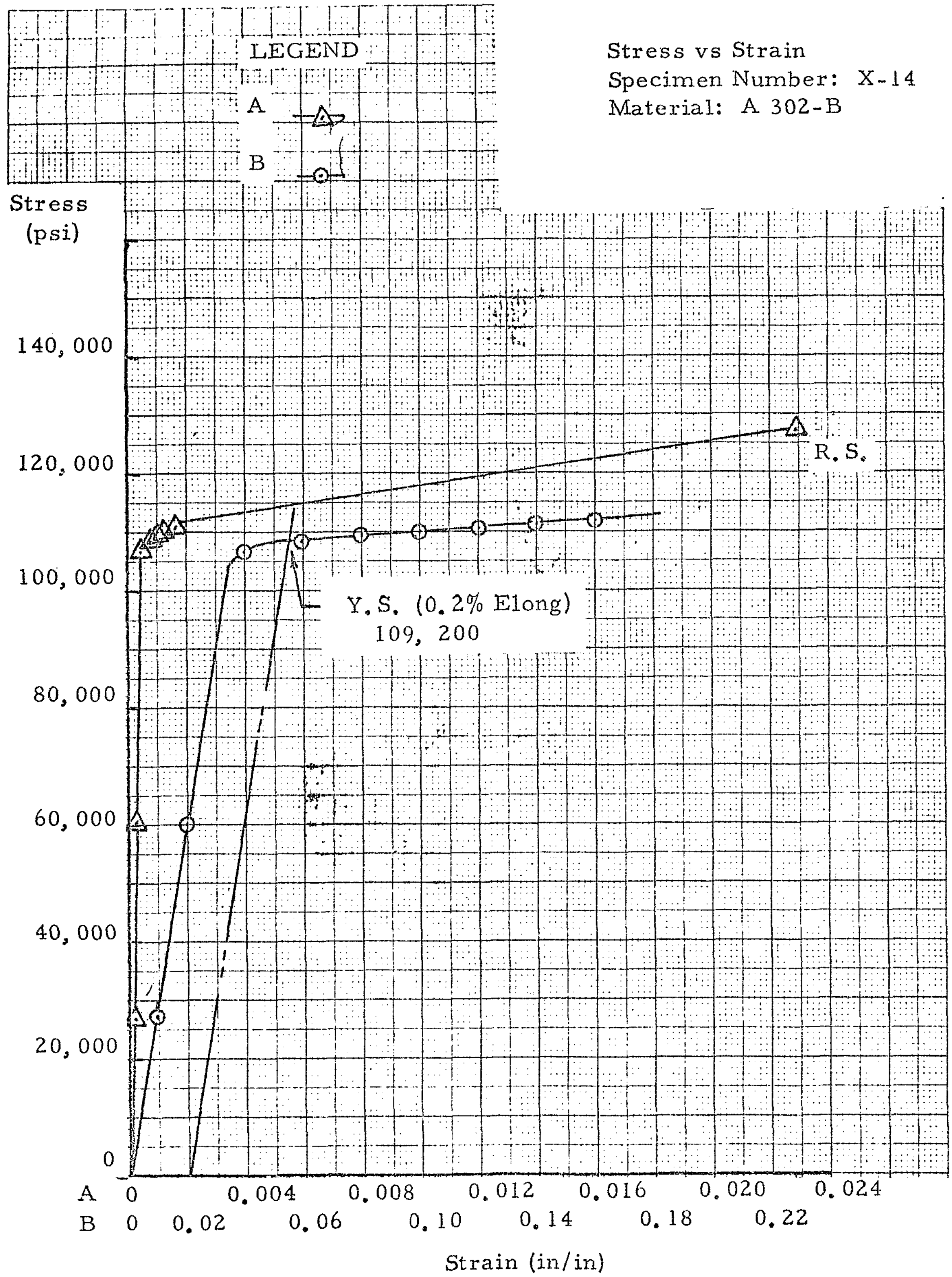


Figure C-13. Stress vs Strain Specimen Number X-14.

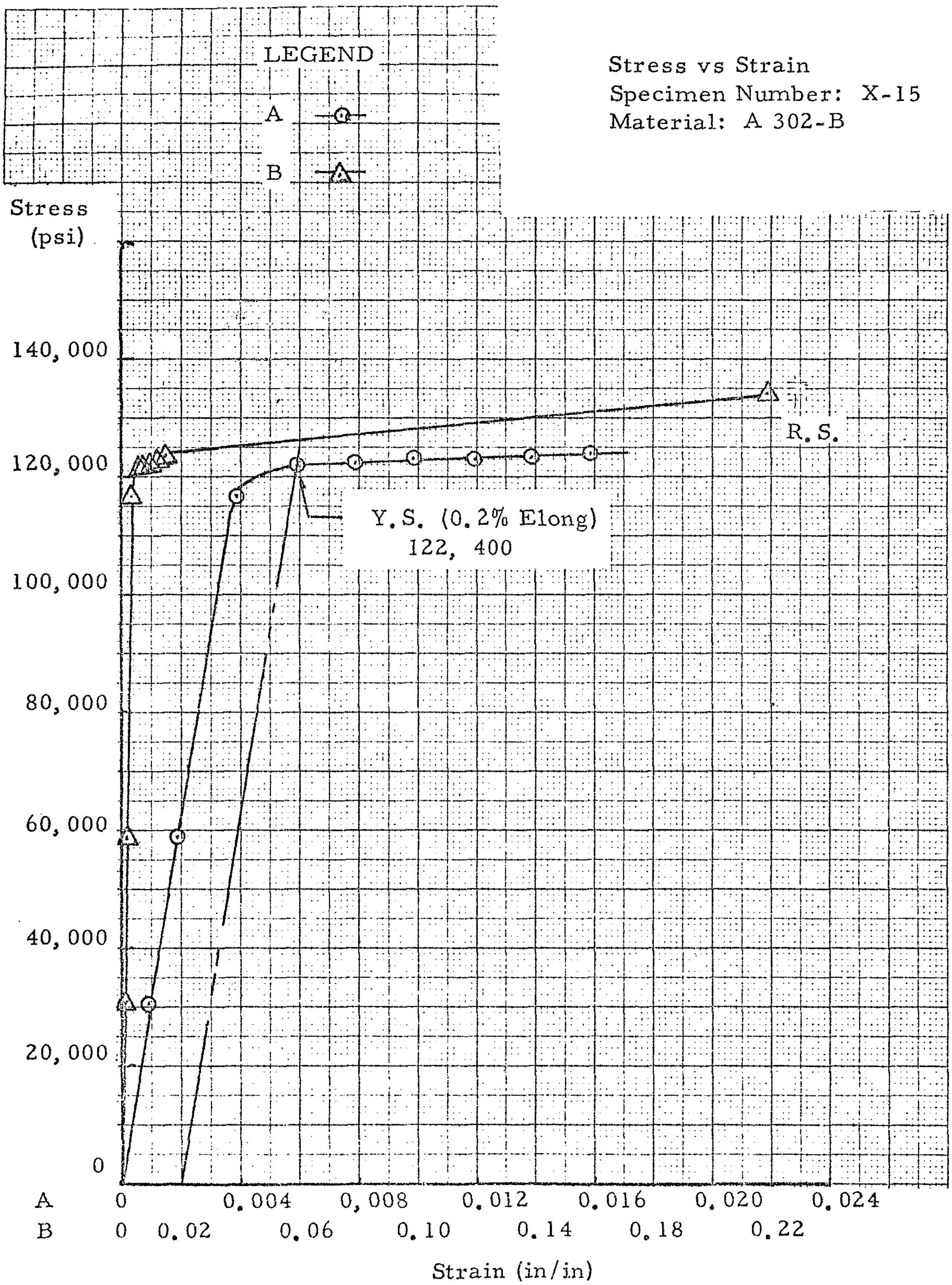


Figure C-14, Stress vs Strain Specimen Number X-15.

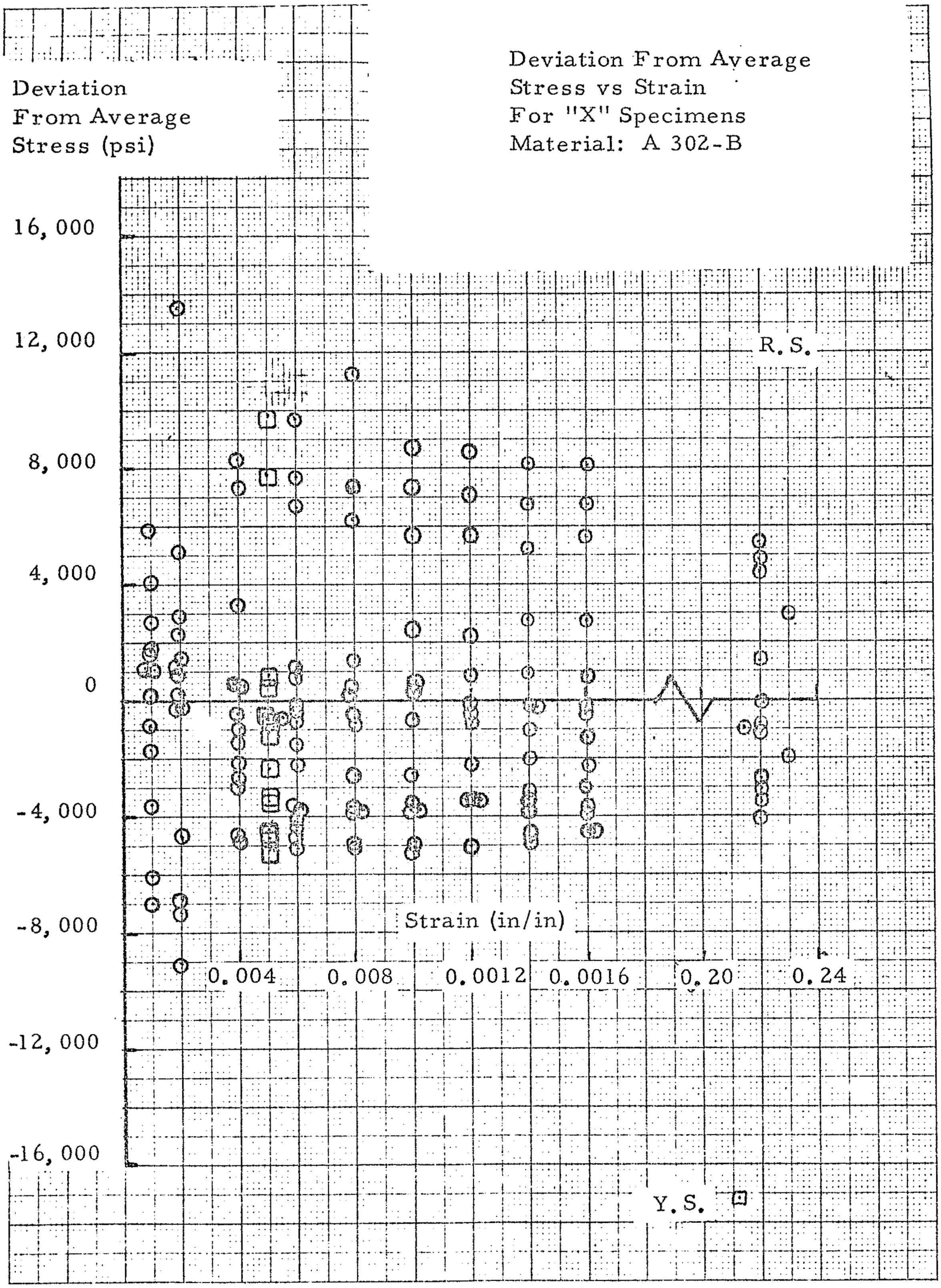


Figure C-15. Deviation From Average Stress vs Strain for X Specimens.

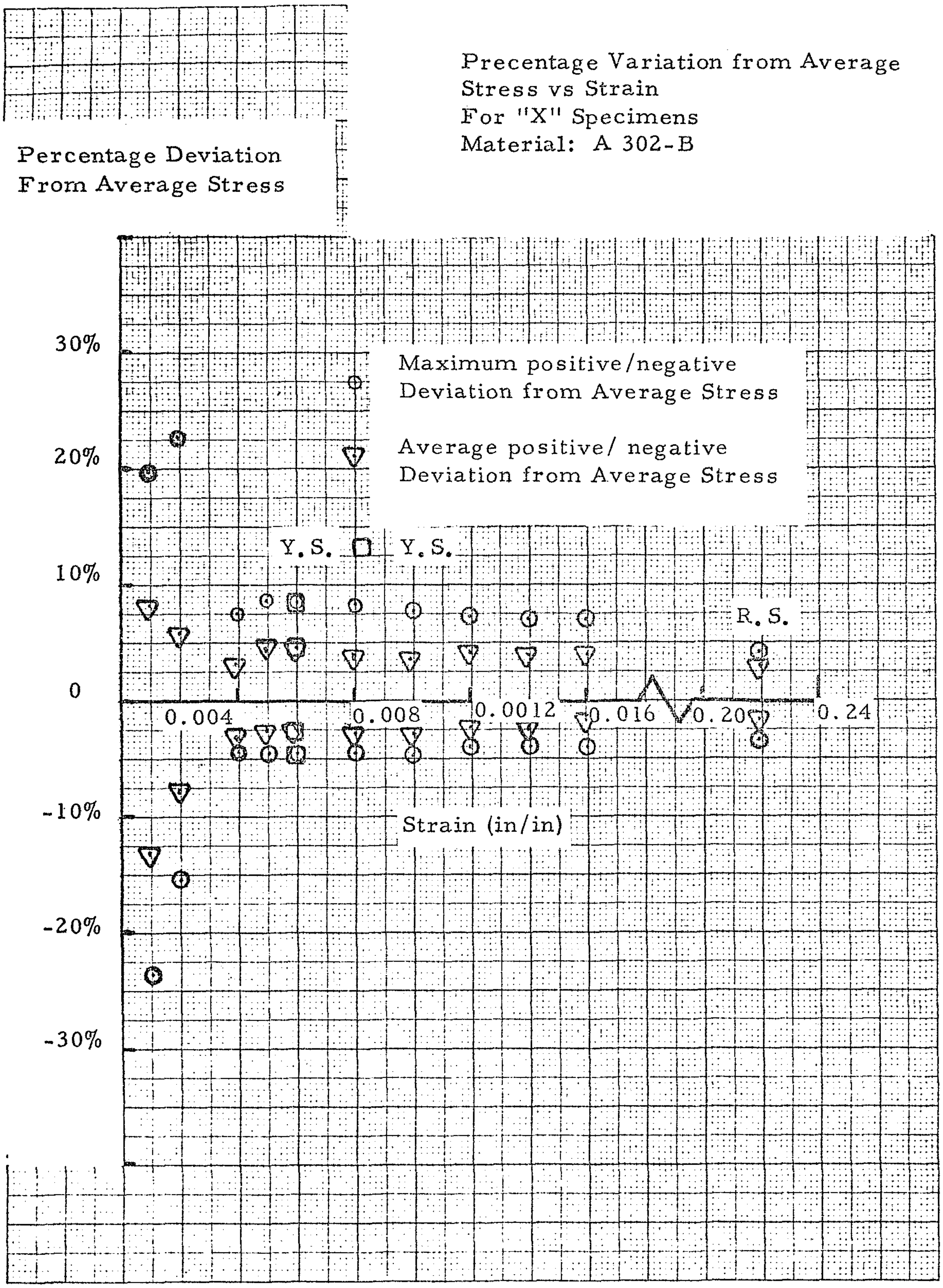


Figure C-16. Percentage Deviation from Average Stress vs Strain for X Specimens

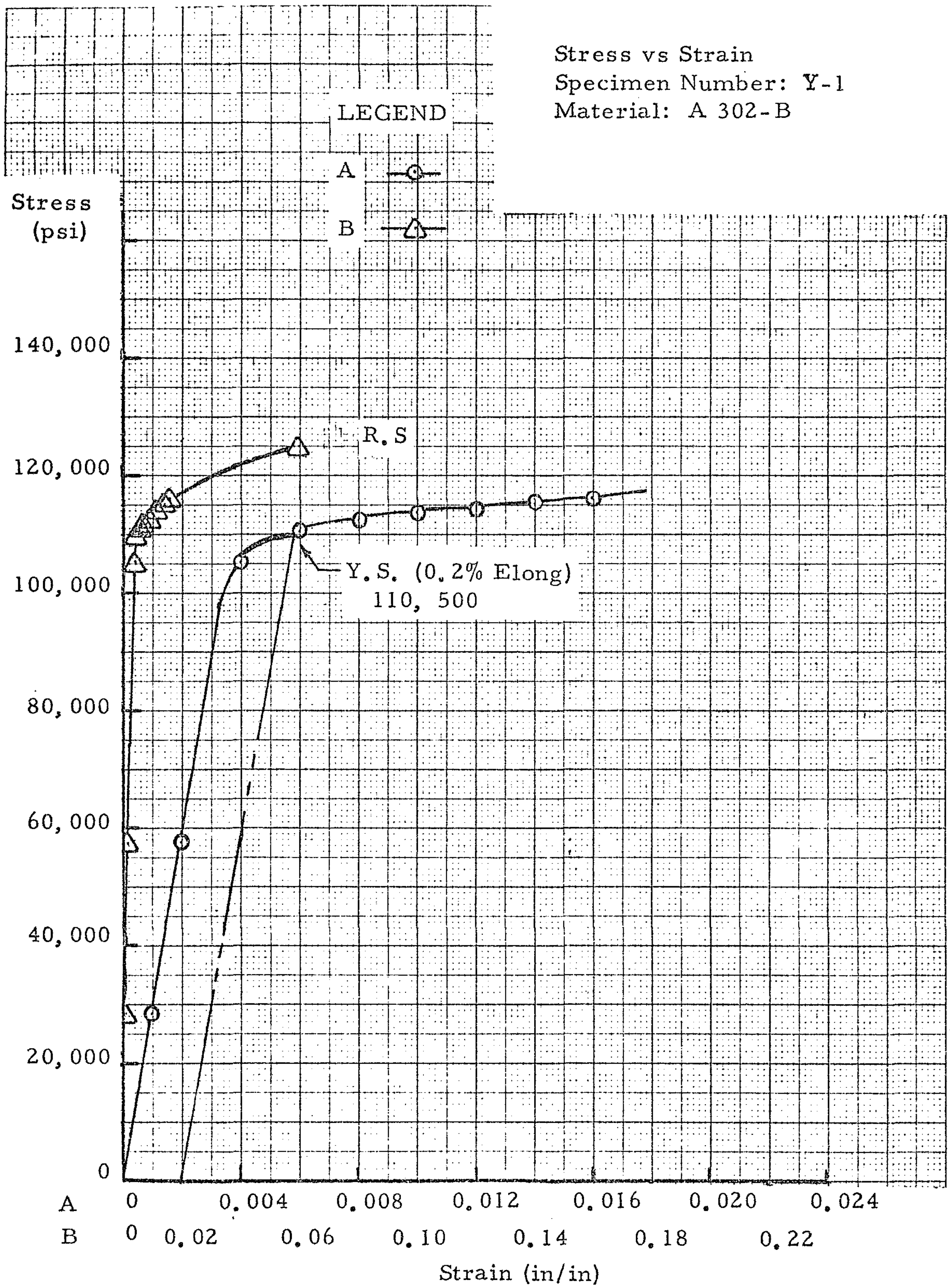


Figure C-17. Stress vs Strain Specimen Number Y-1.

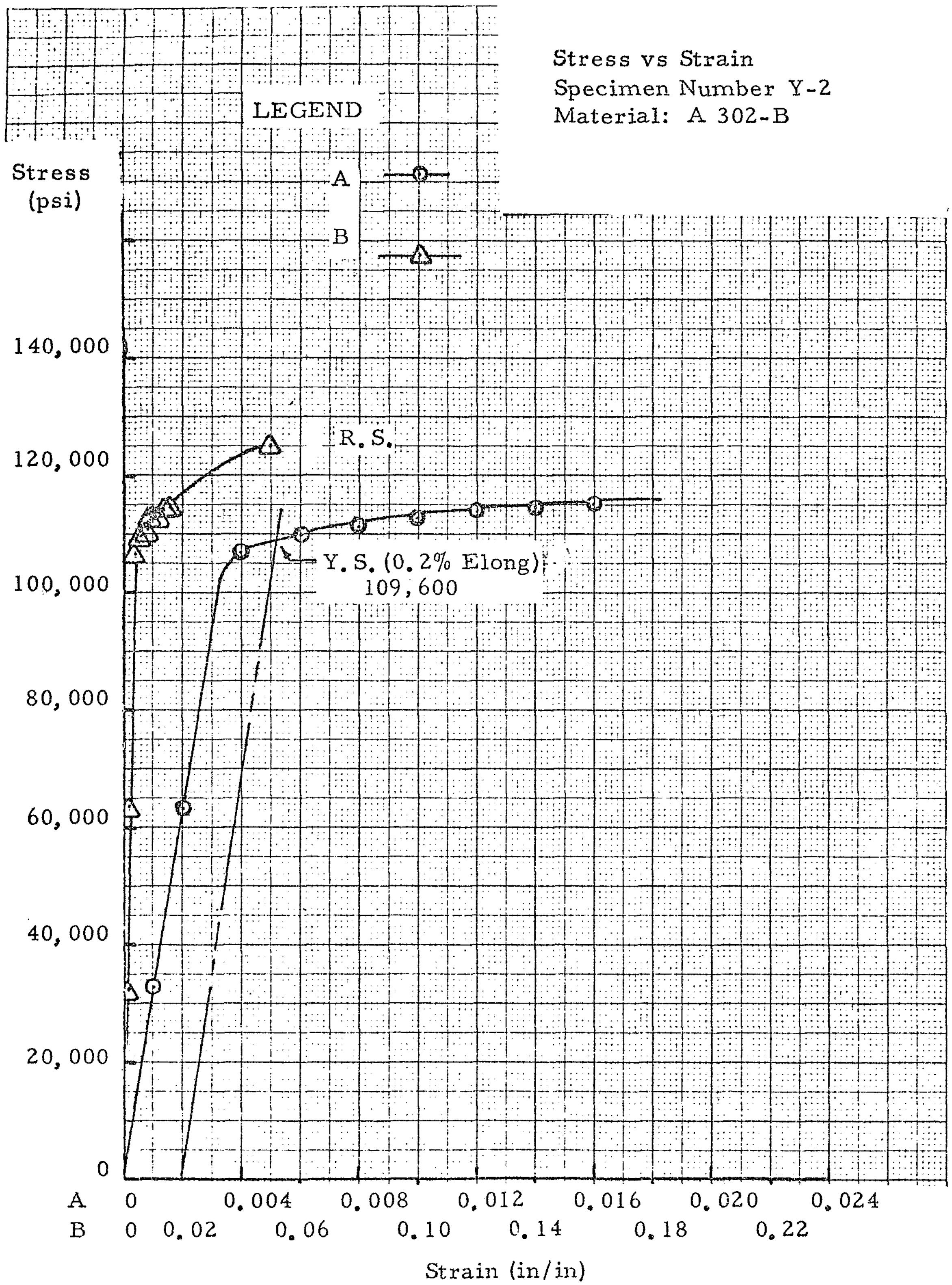


Figure C-18. Stress vs Strain, Specimen Number Y-2.

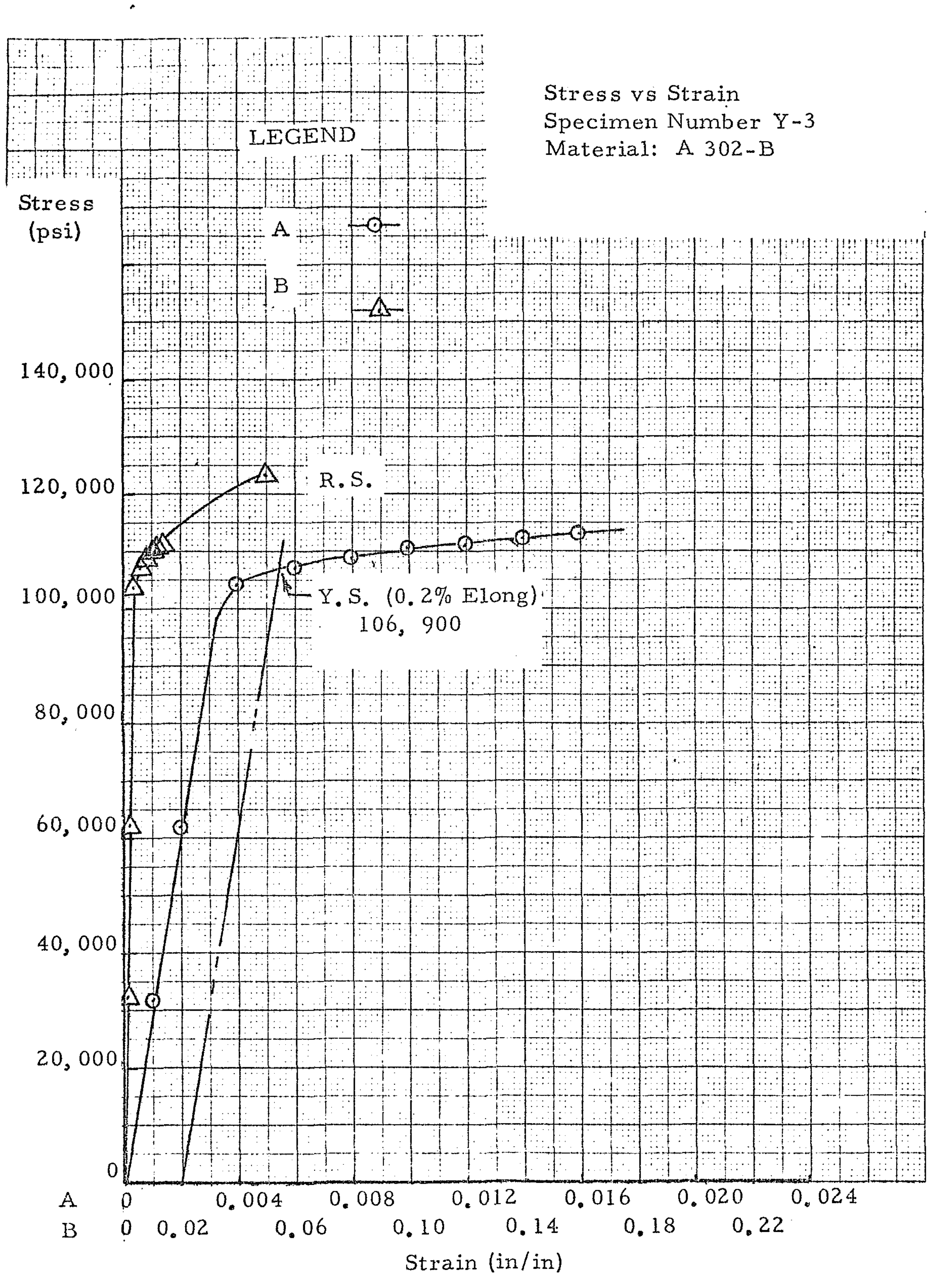


Figure C-19. Stress vs Strain, Specimen Number Y-3.

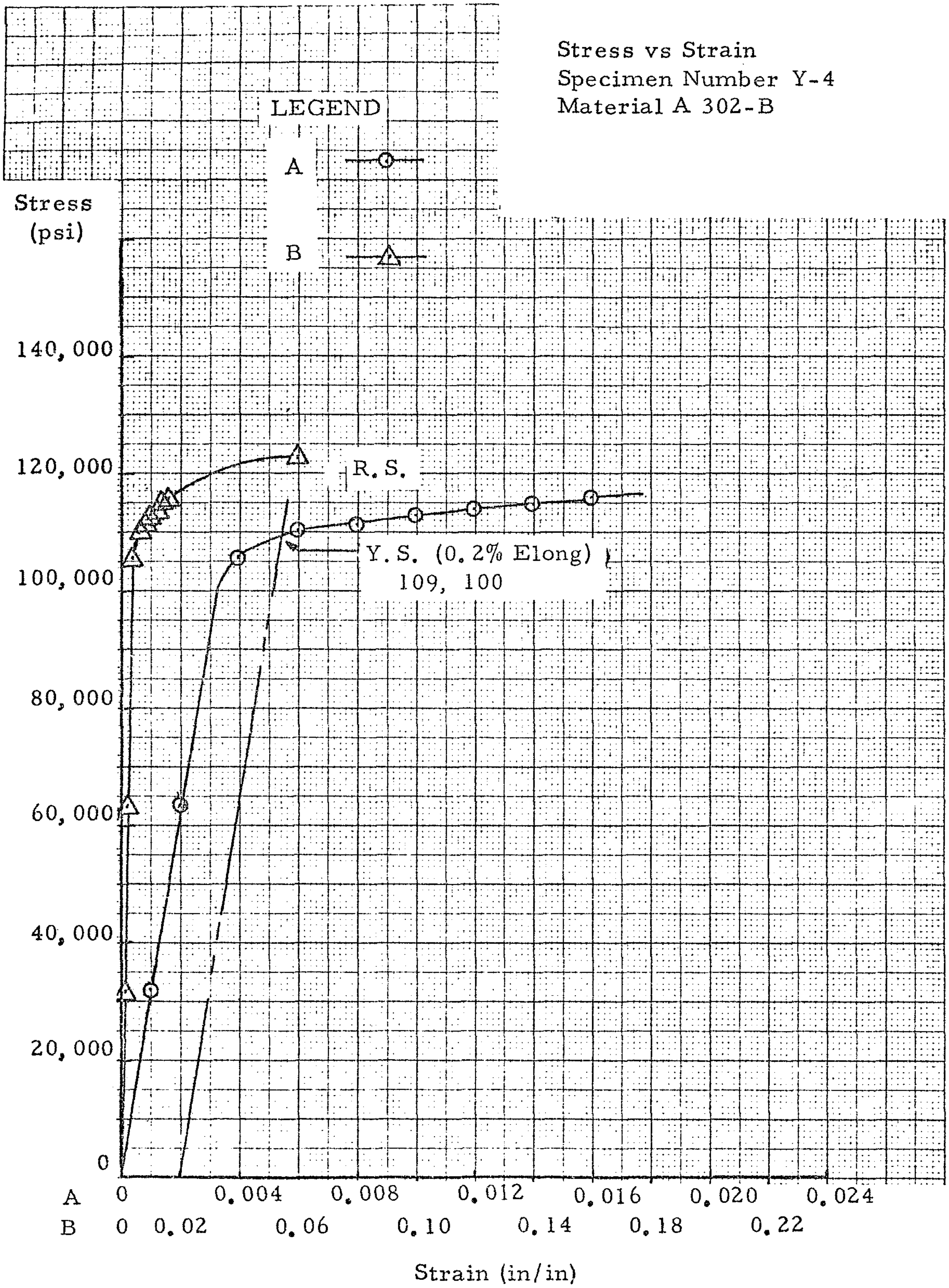


Figure C-20. Stress vs Strain, Specimen Number Y-4

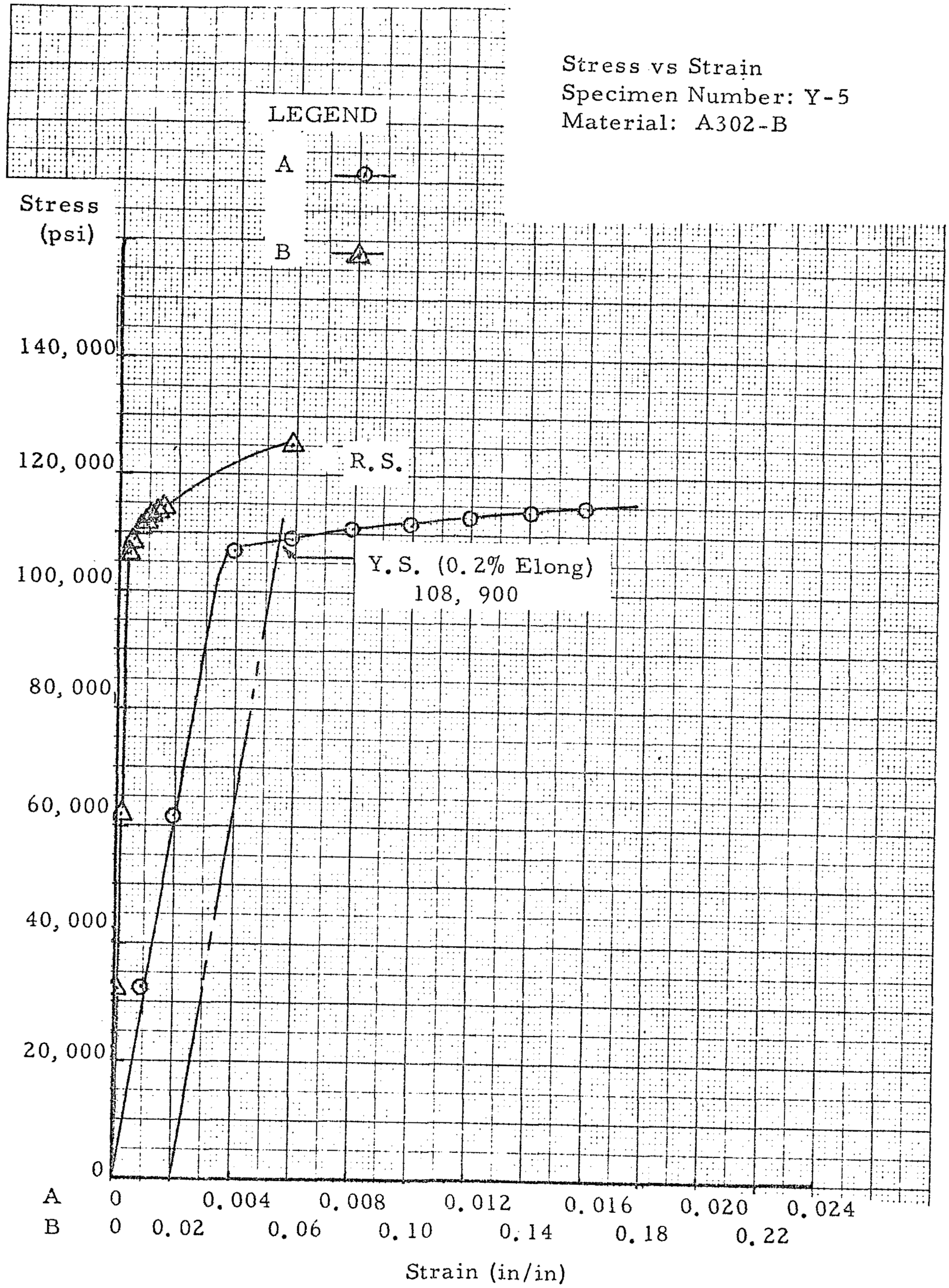


Figure C-21. Stress vs Strain, Specimen Number Y-5.

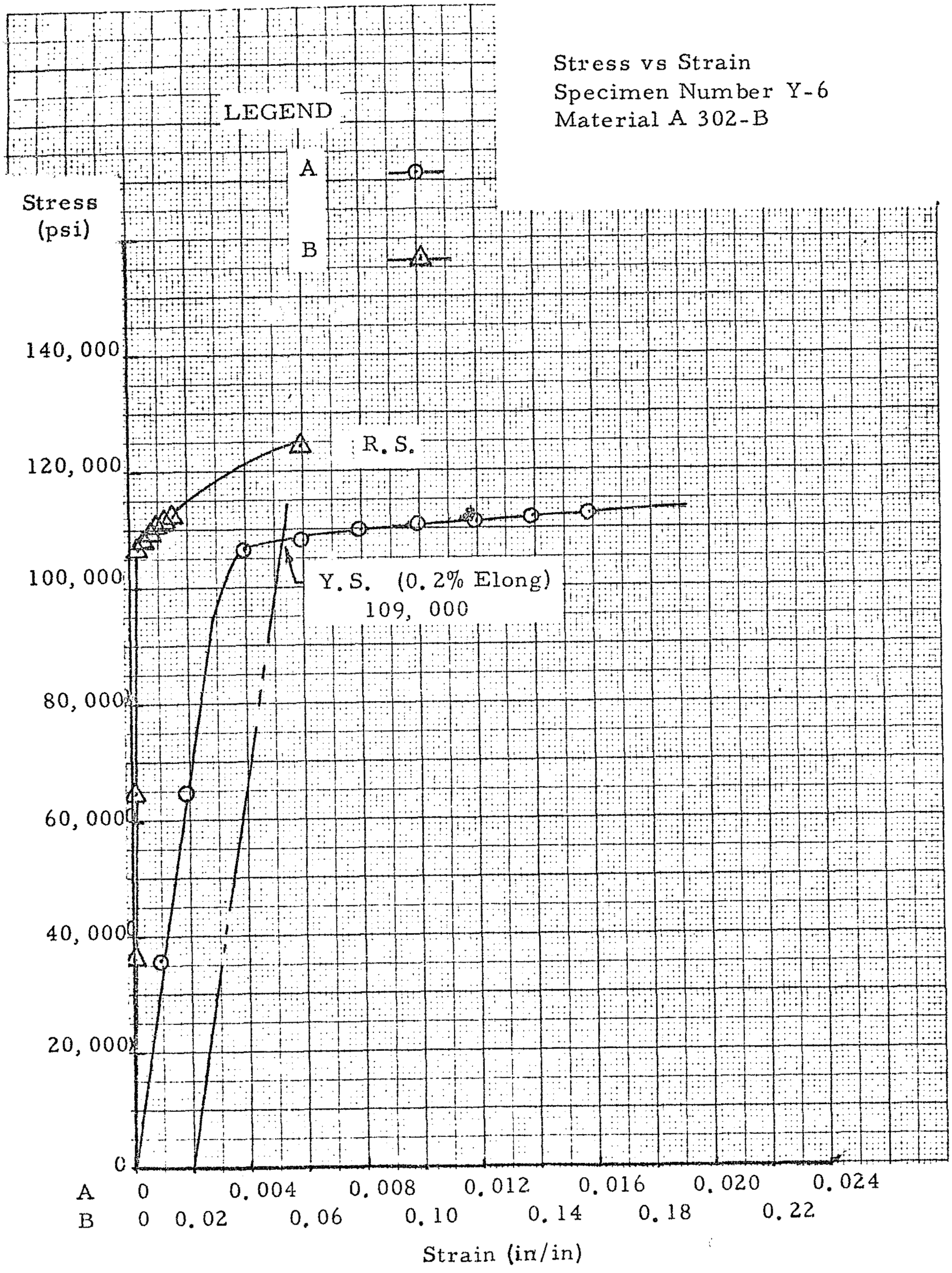


Figure C-22. Stress vs Strain, Specimen Number Y-6.

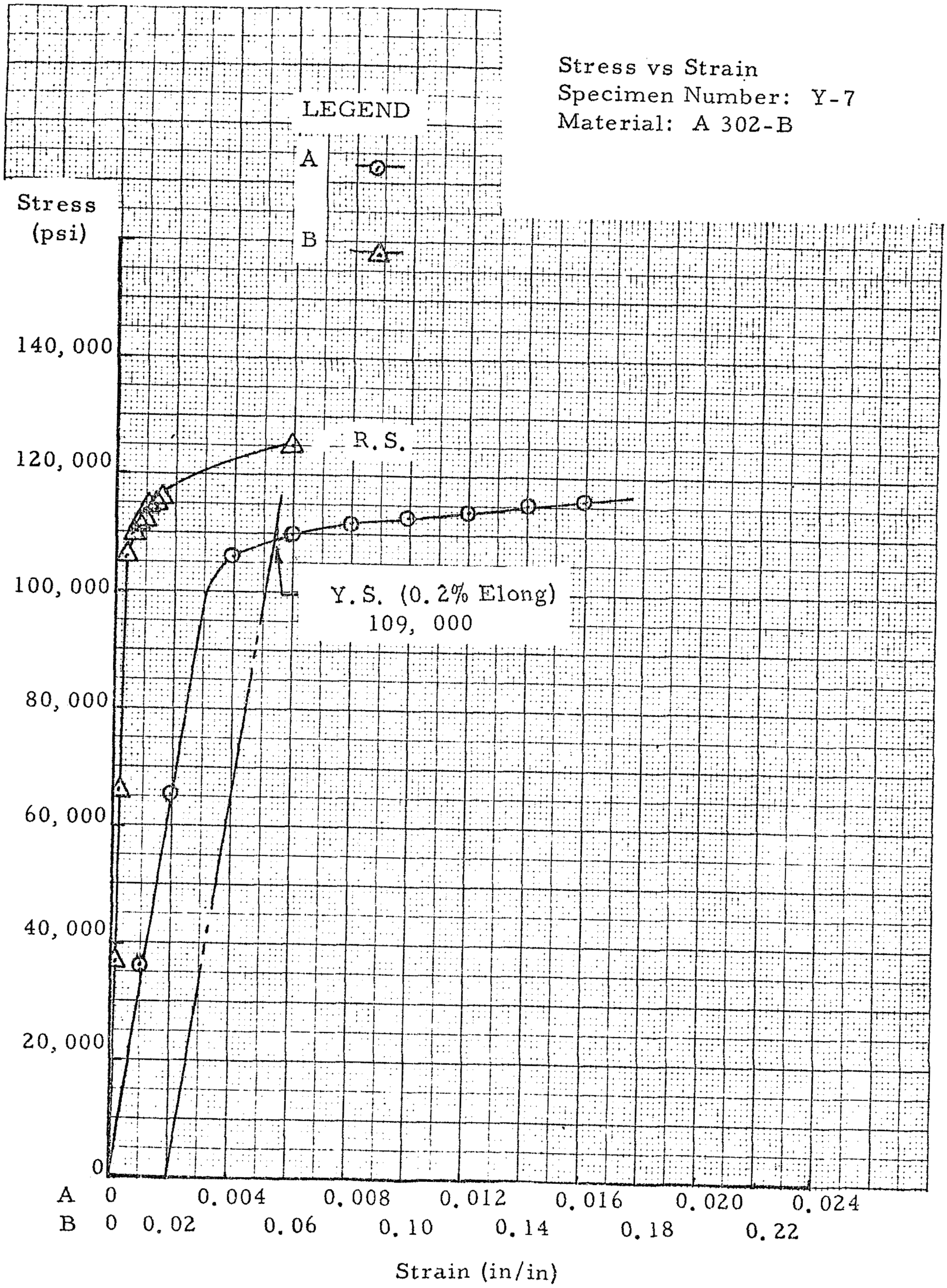


Figure C-23. Stress vs Strain, Specimen Number Y-7

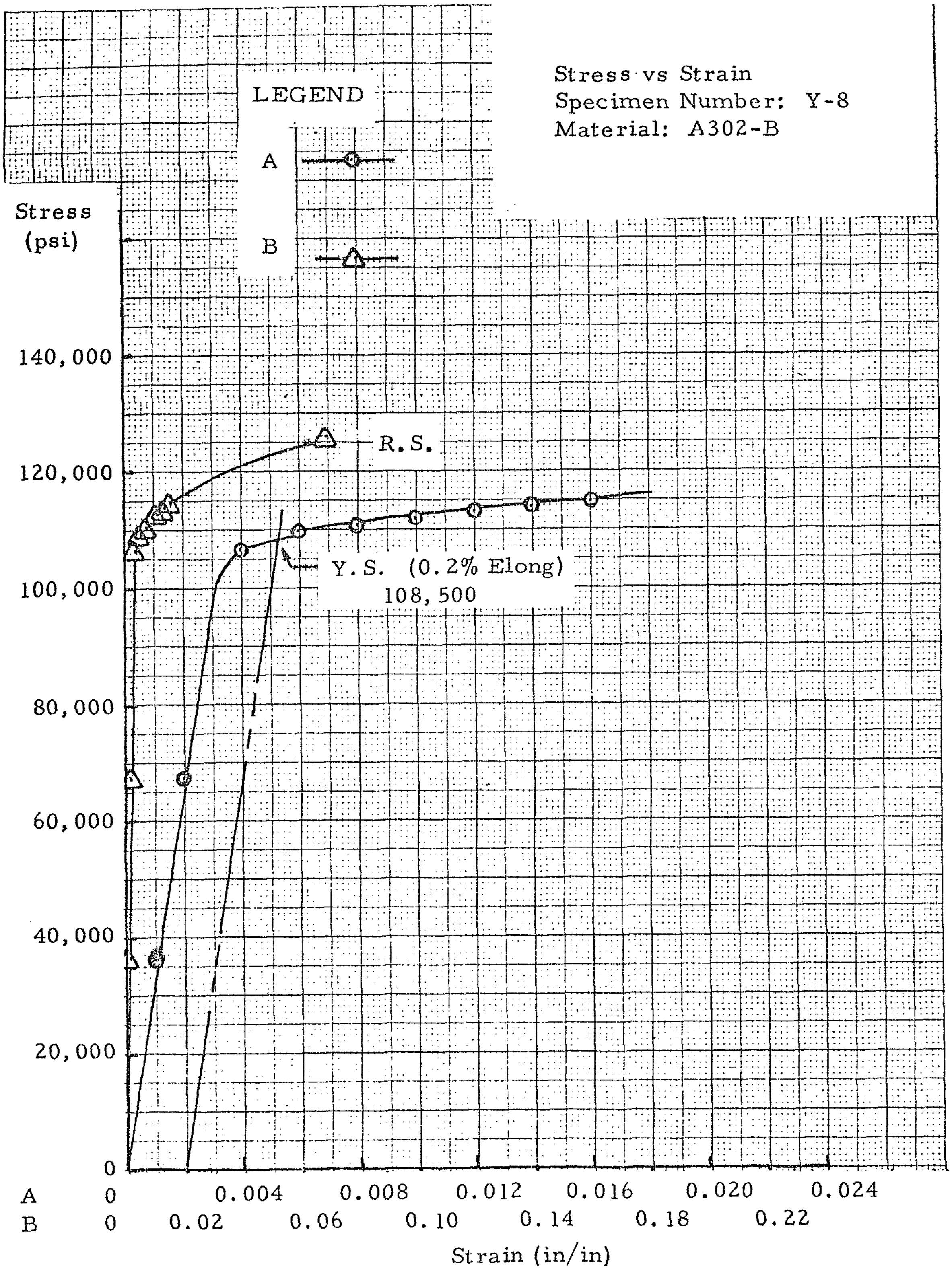


Figure C-24. Stress vs Strain, Specimen Number Y-8

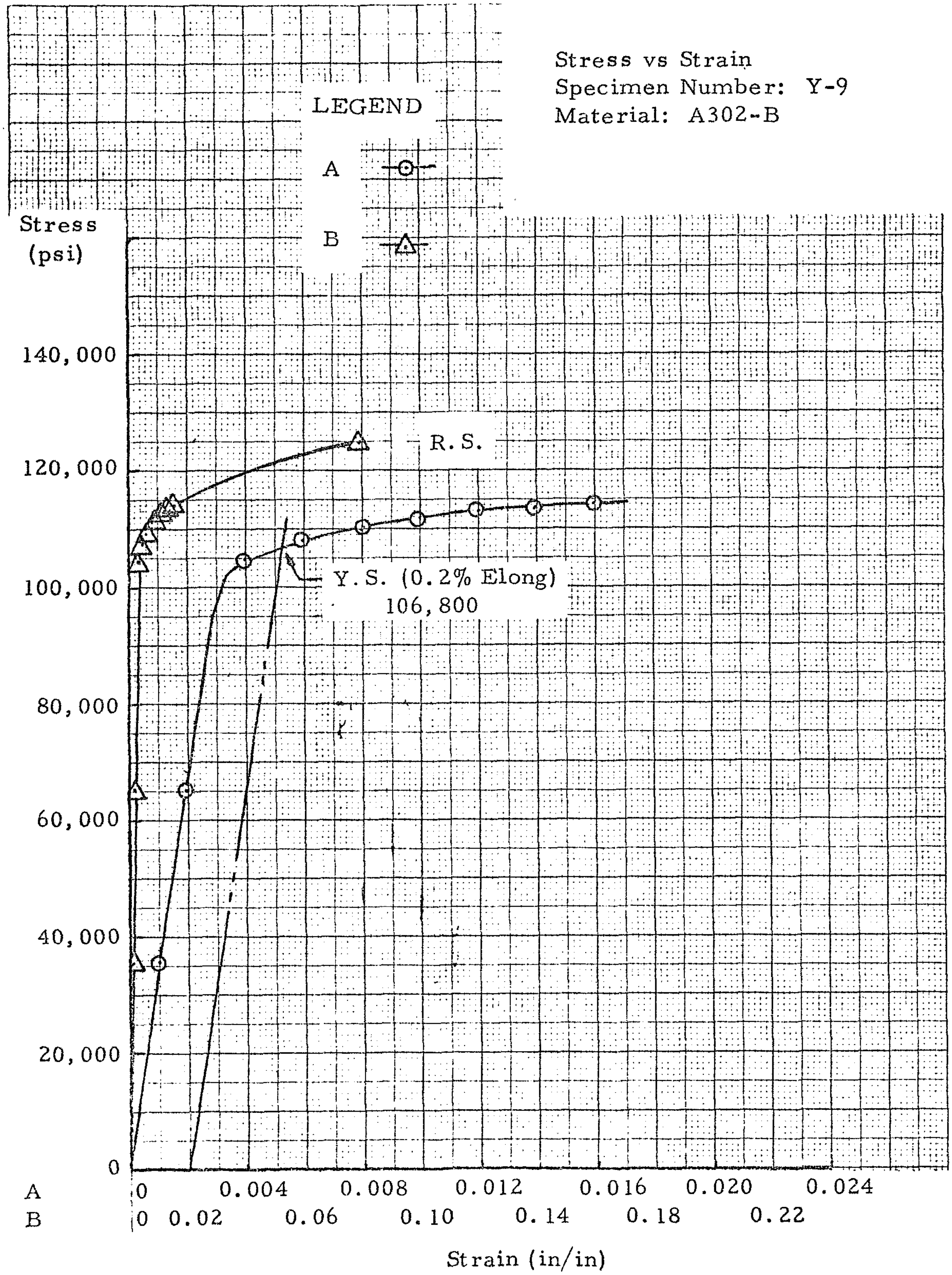


Figure C-25. Stress vs Strain, Specimen Number Y-9.

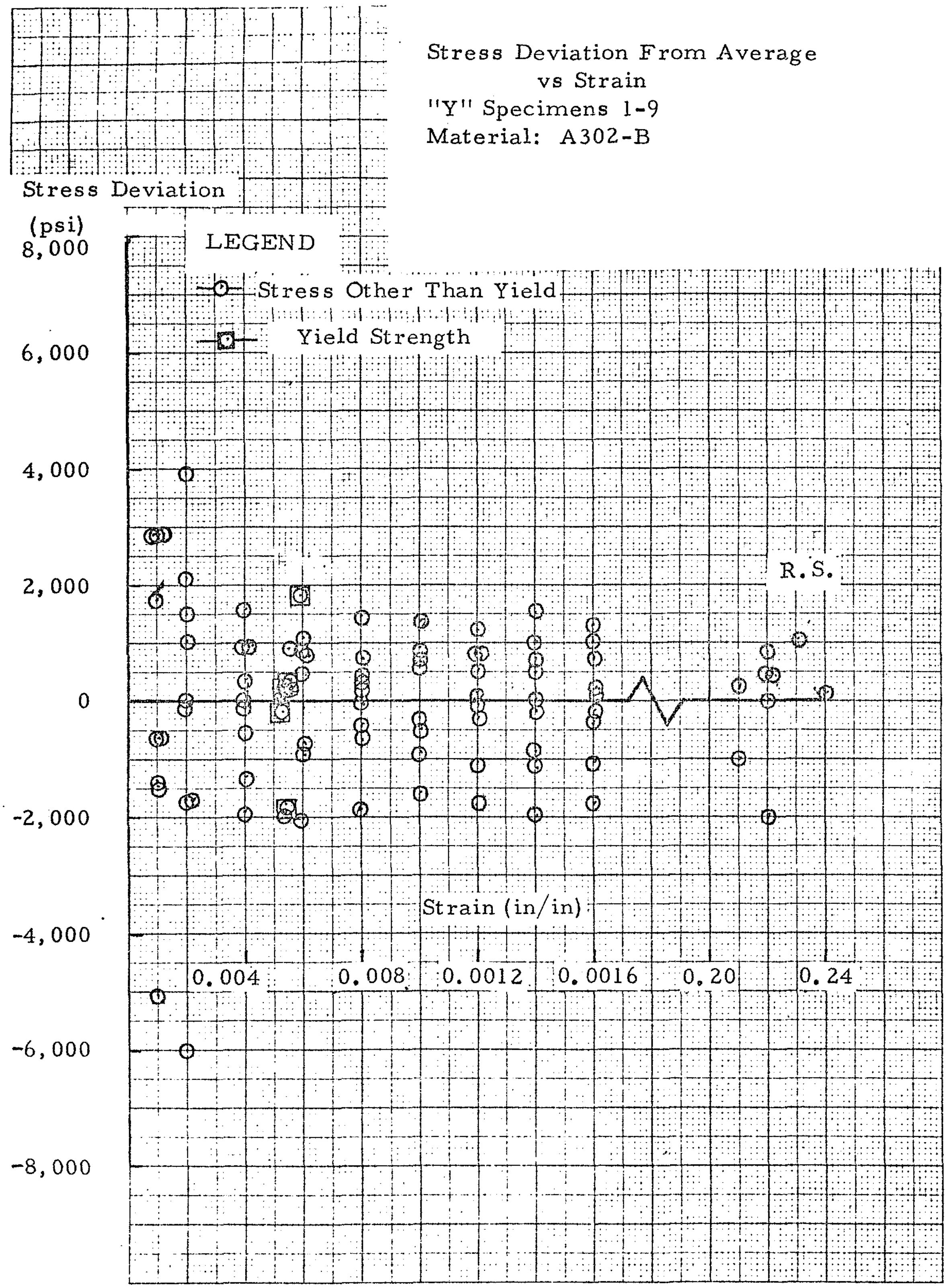


Figure C-26. Deviation From Average Stress vs Strain for Y Specimens

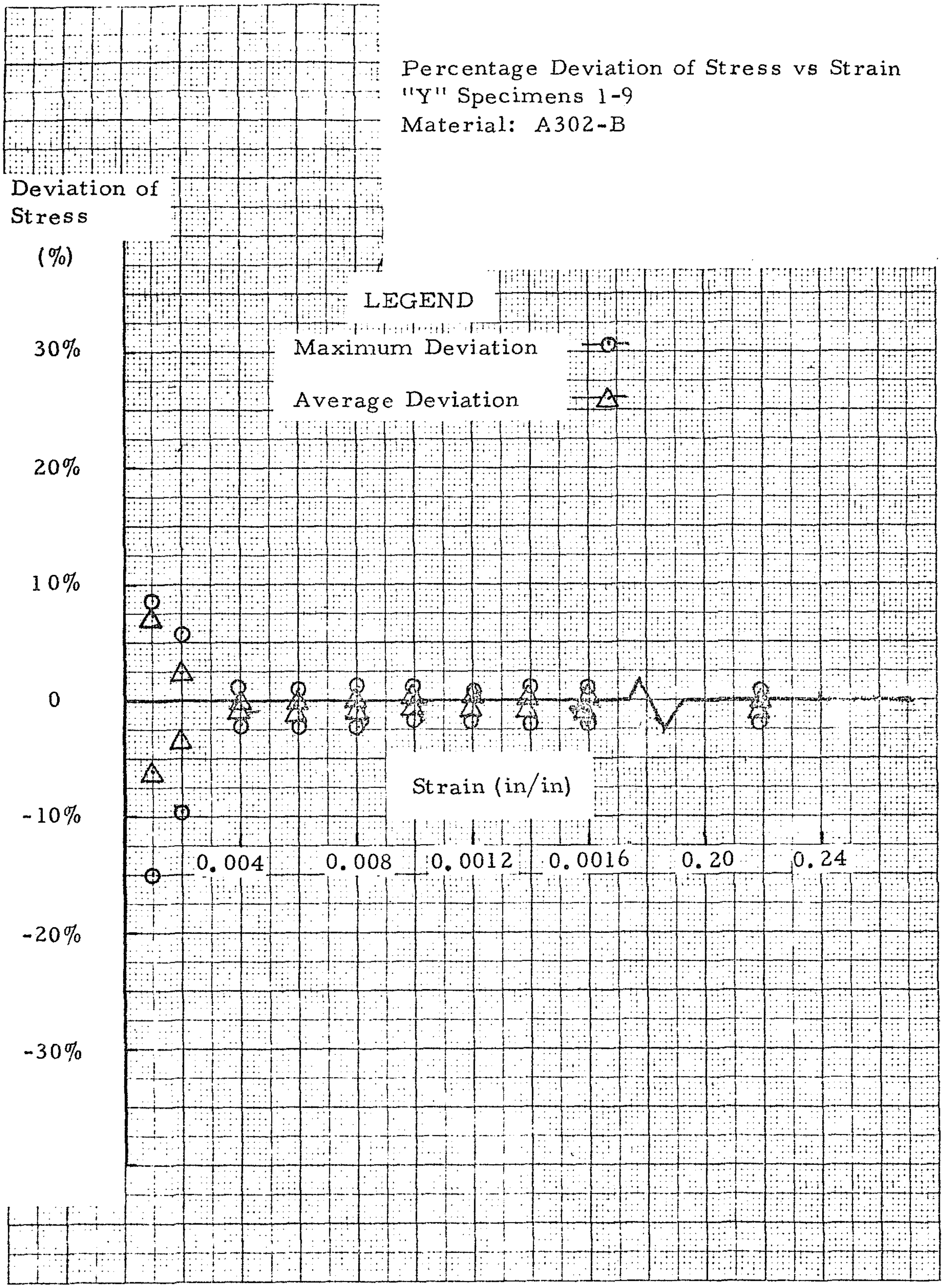


Figure C-27. Percentage Deviation from Average Stress vs Strain for Y Specimens

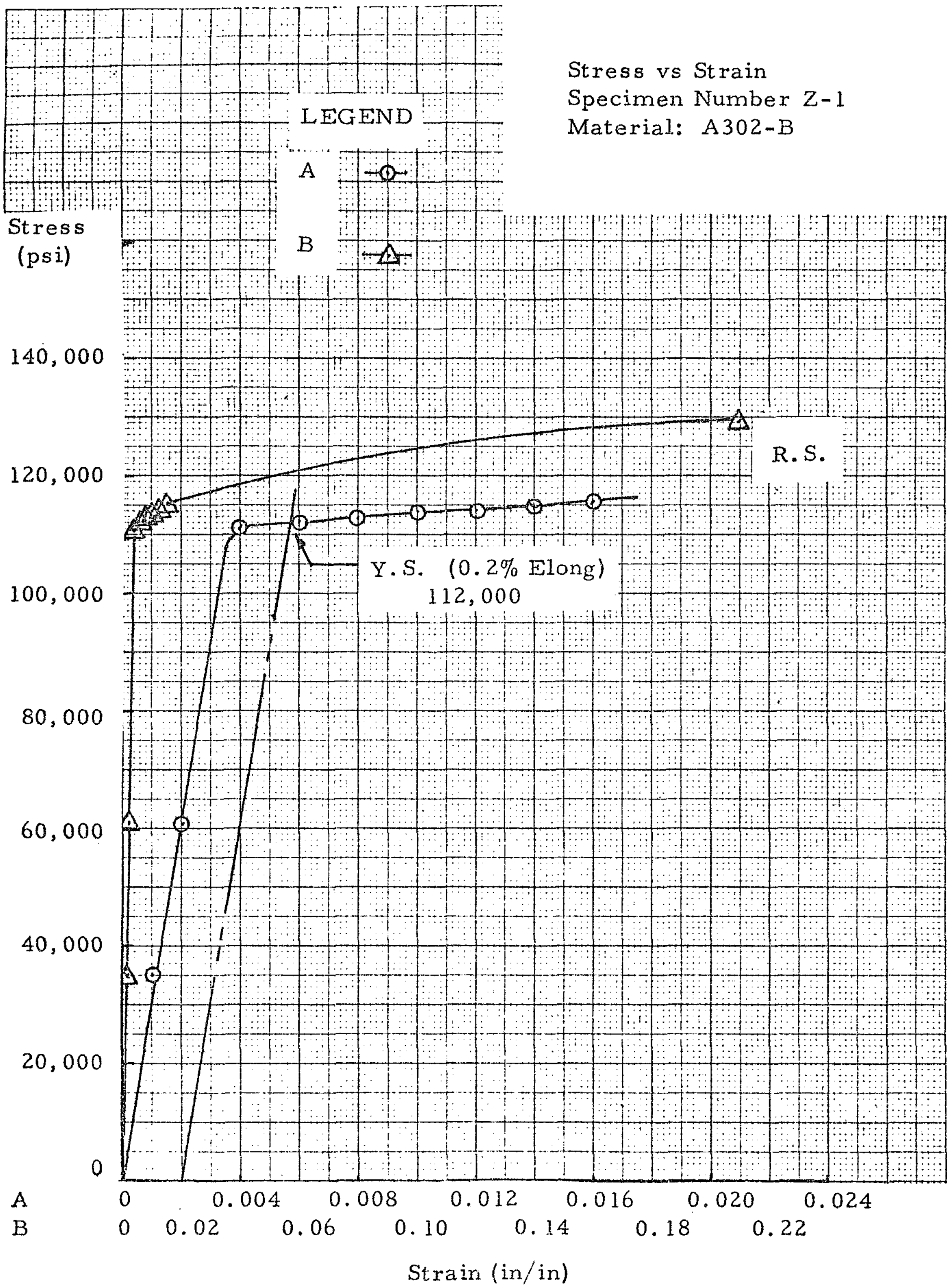


Figure C-28. Stress vs Strain, Specimen Number Z-1

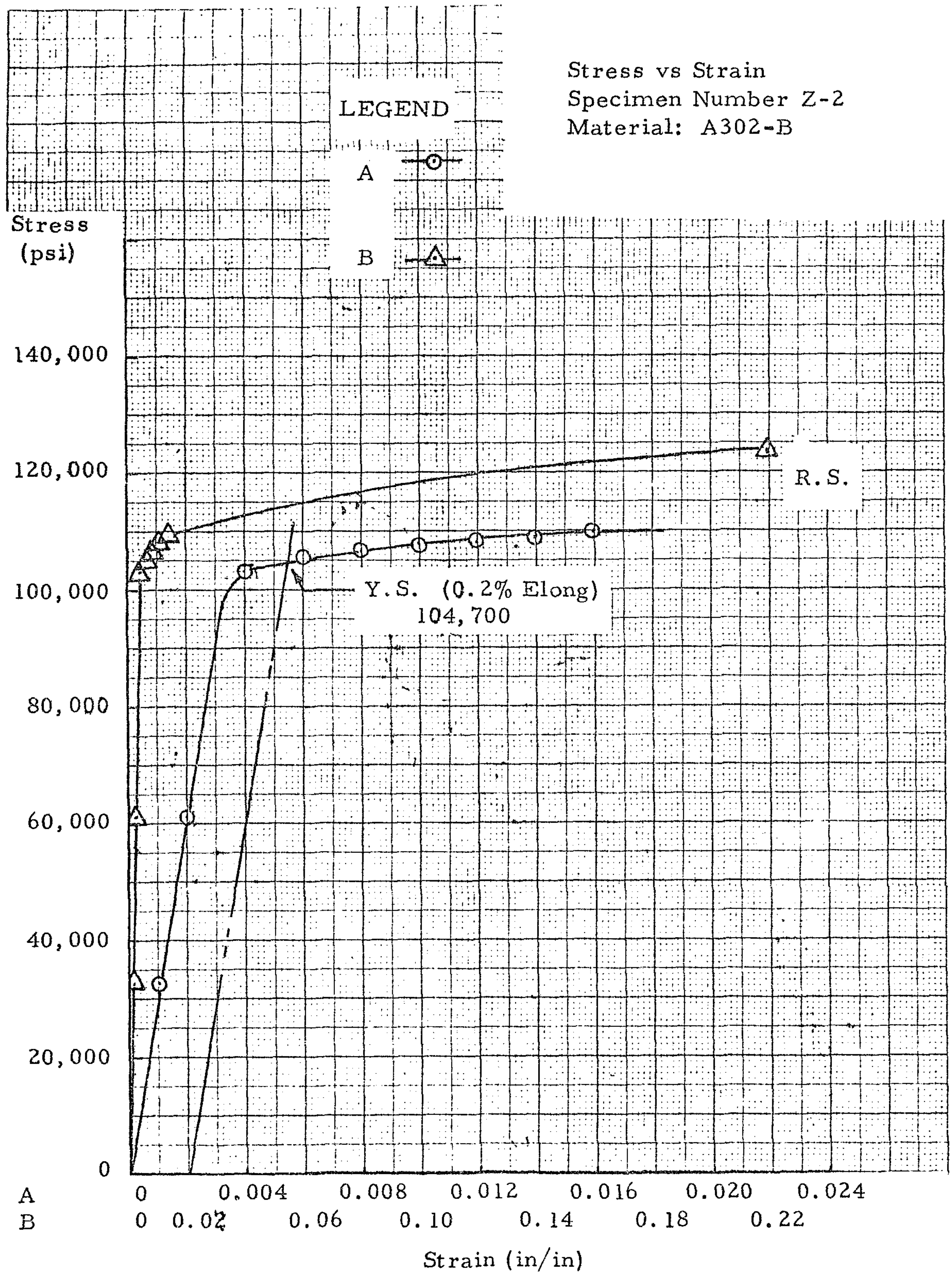


Figure C-29. Stress vs Strain, Specimen Number Z-2

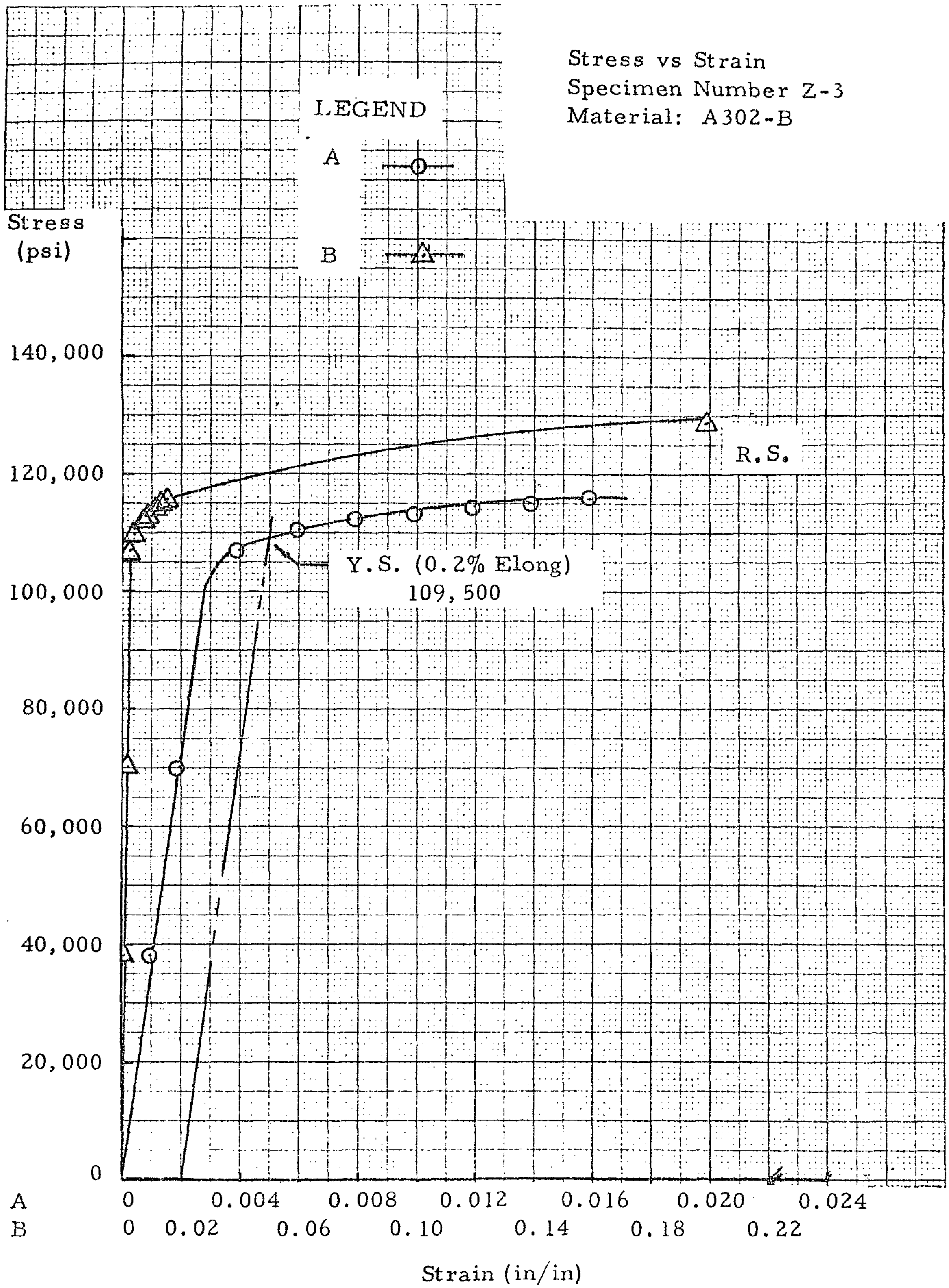


Figure C-30. Stress vs Strain, Specimen Number Z-3

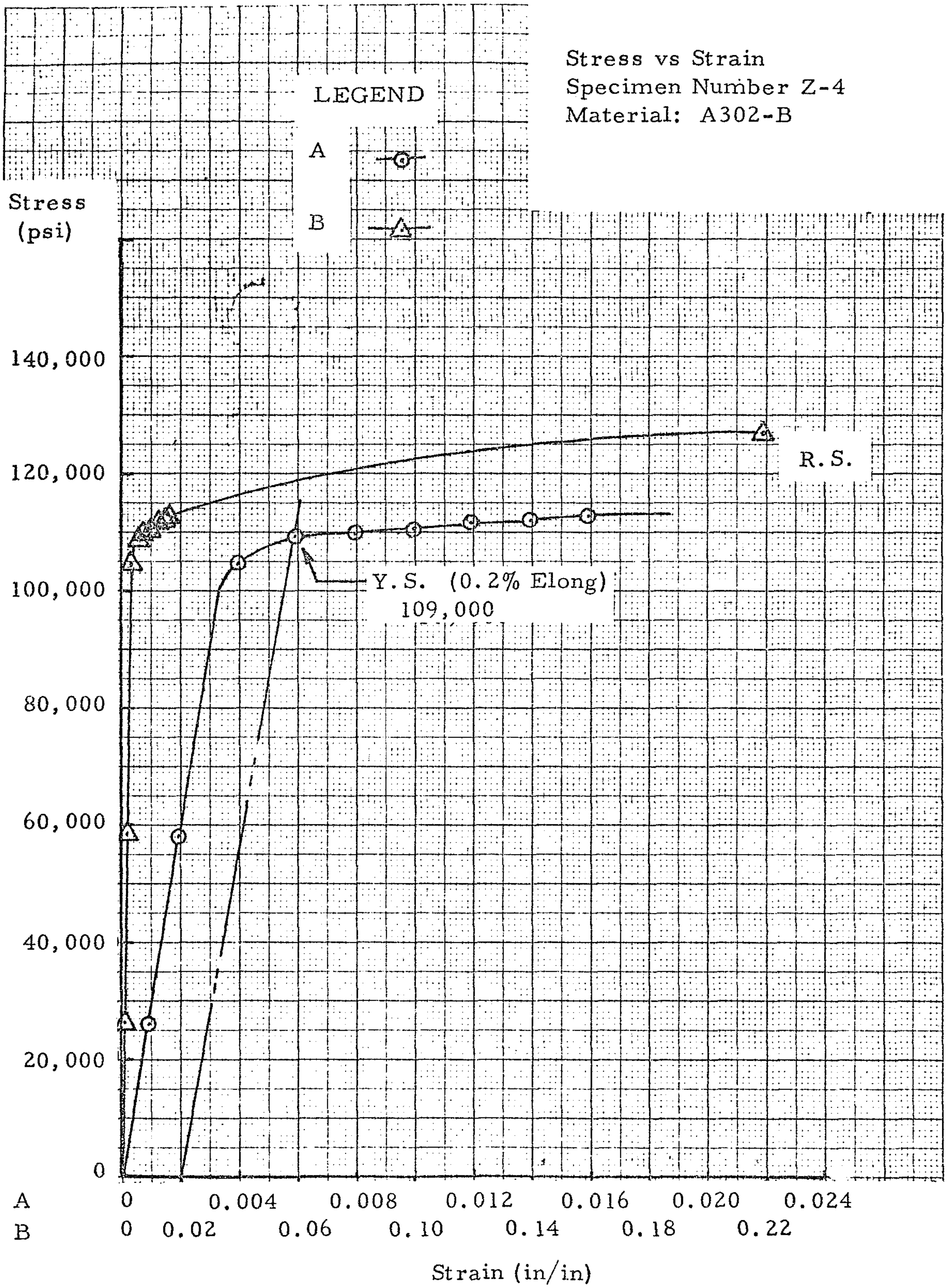


Figure C-31. Stress vs Strain, Specimen Number Z-4

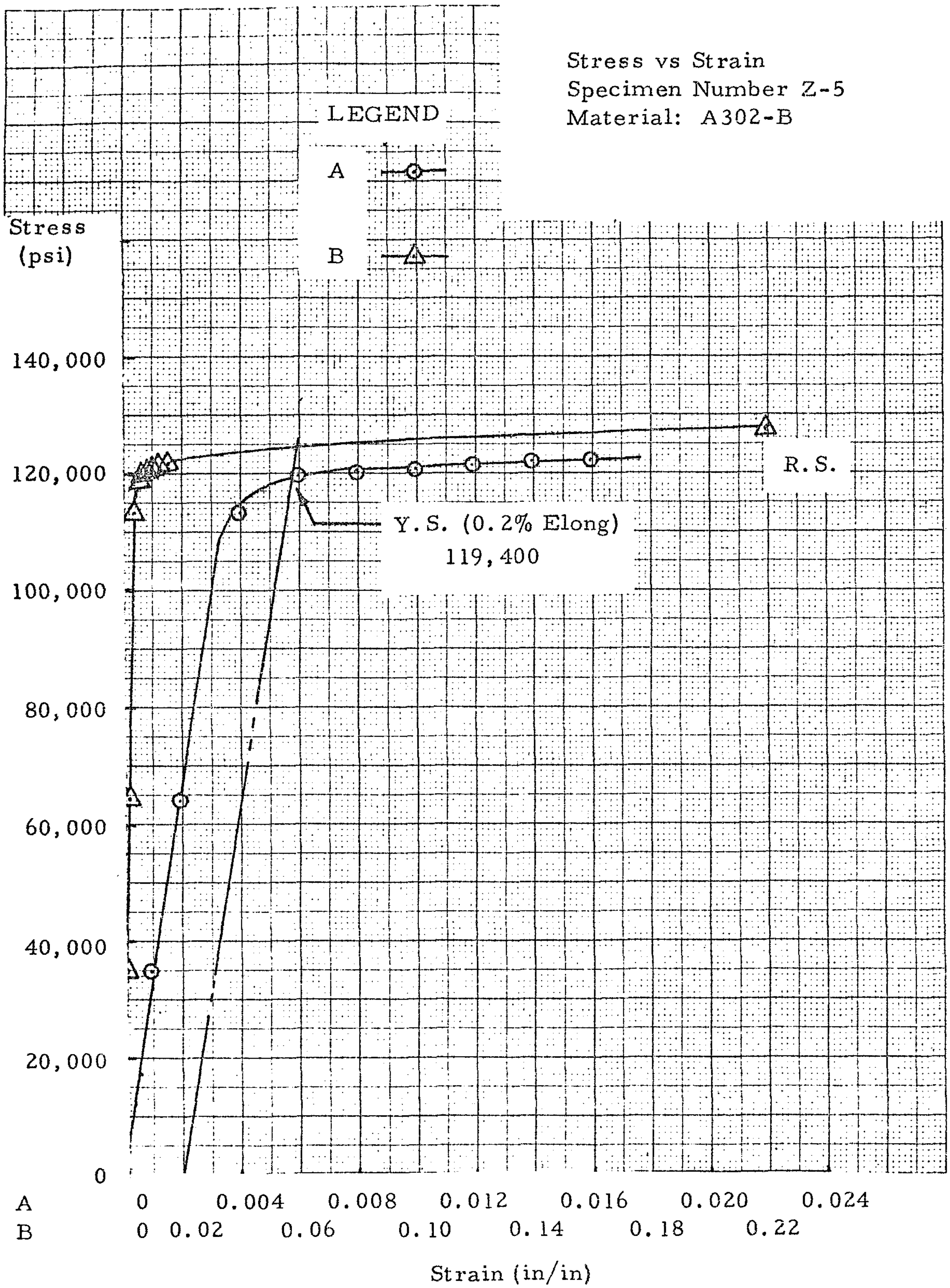


Figure C-32. Stress vs Strain, Specimen Number Z-5

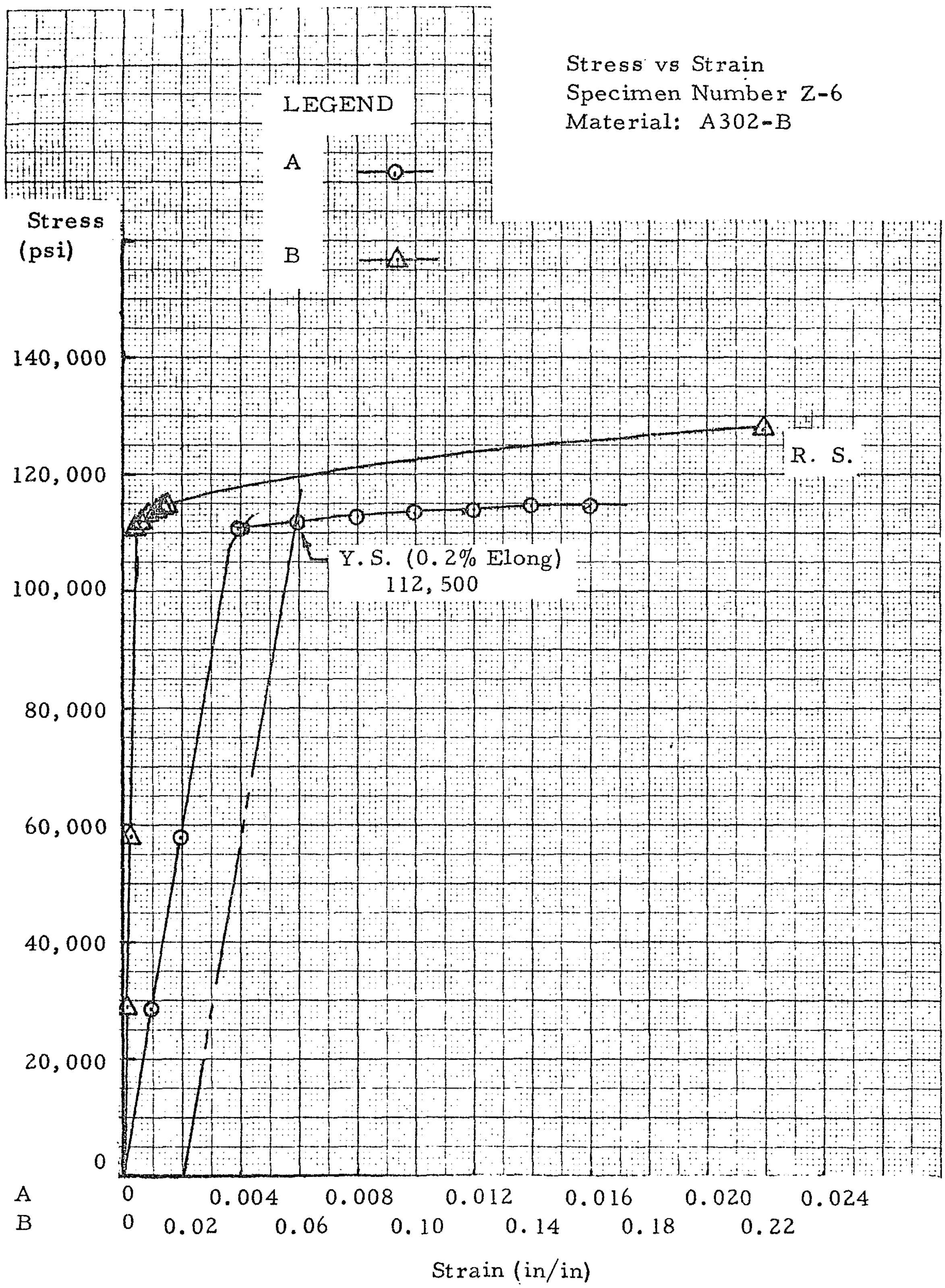


Figure C-33. Stress vs Strain, Specimen Number Z-6

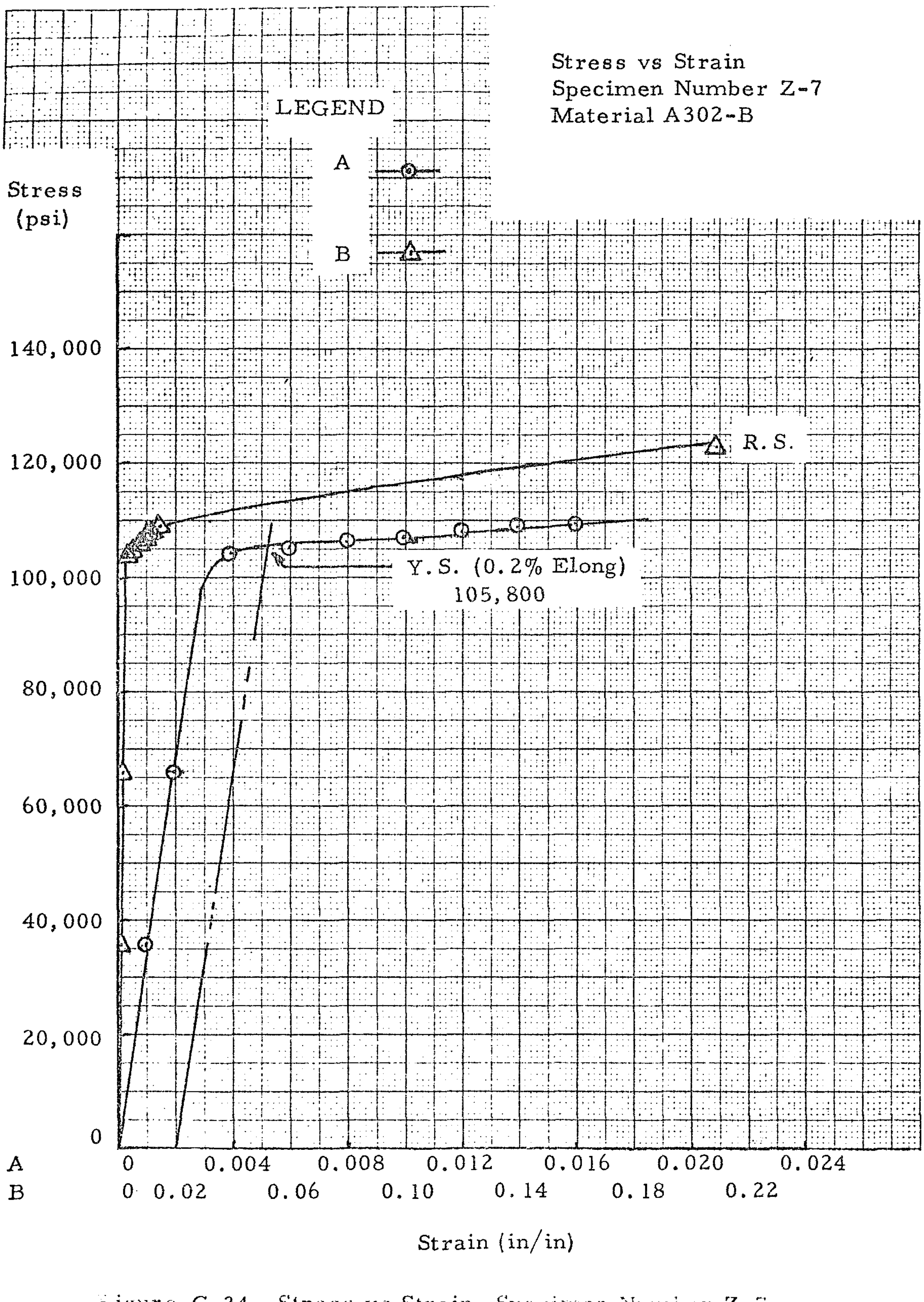


Figure C-34. Stress vs Strain, Specimen Number Z-7

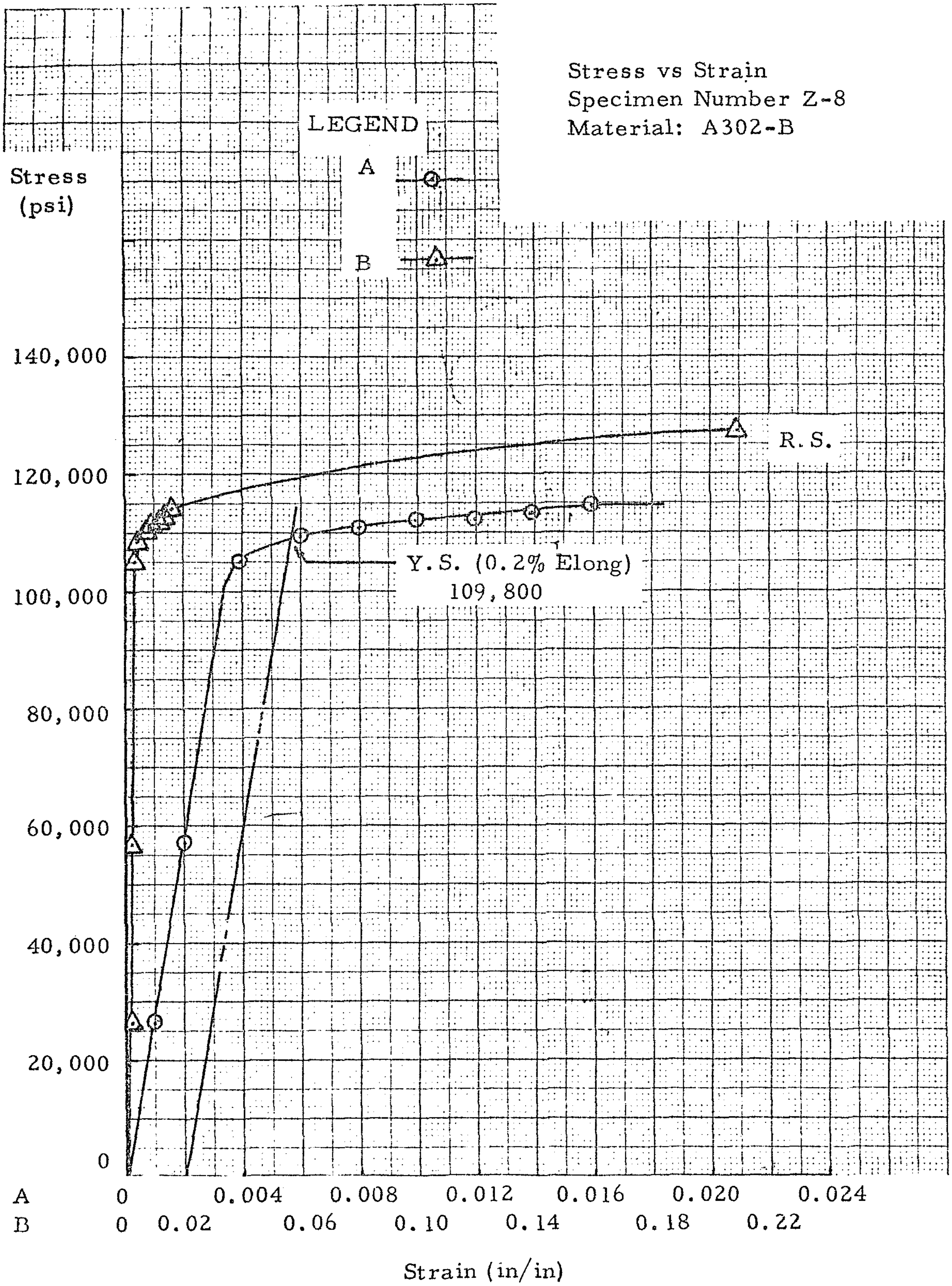


Figure C-35. Stress vs Strain, Specimen Number Z-8

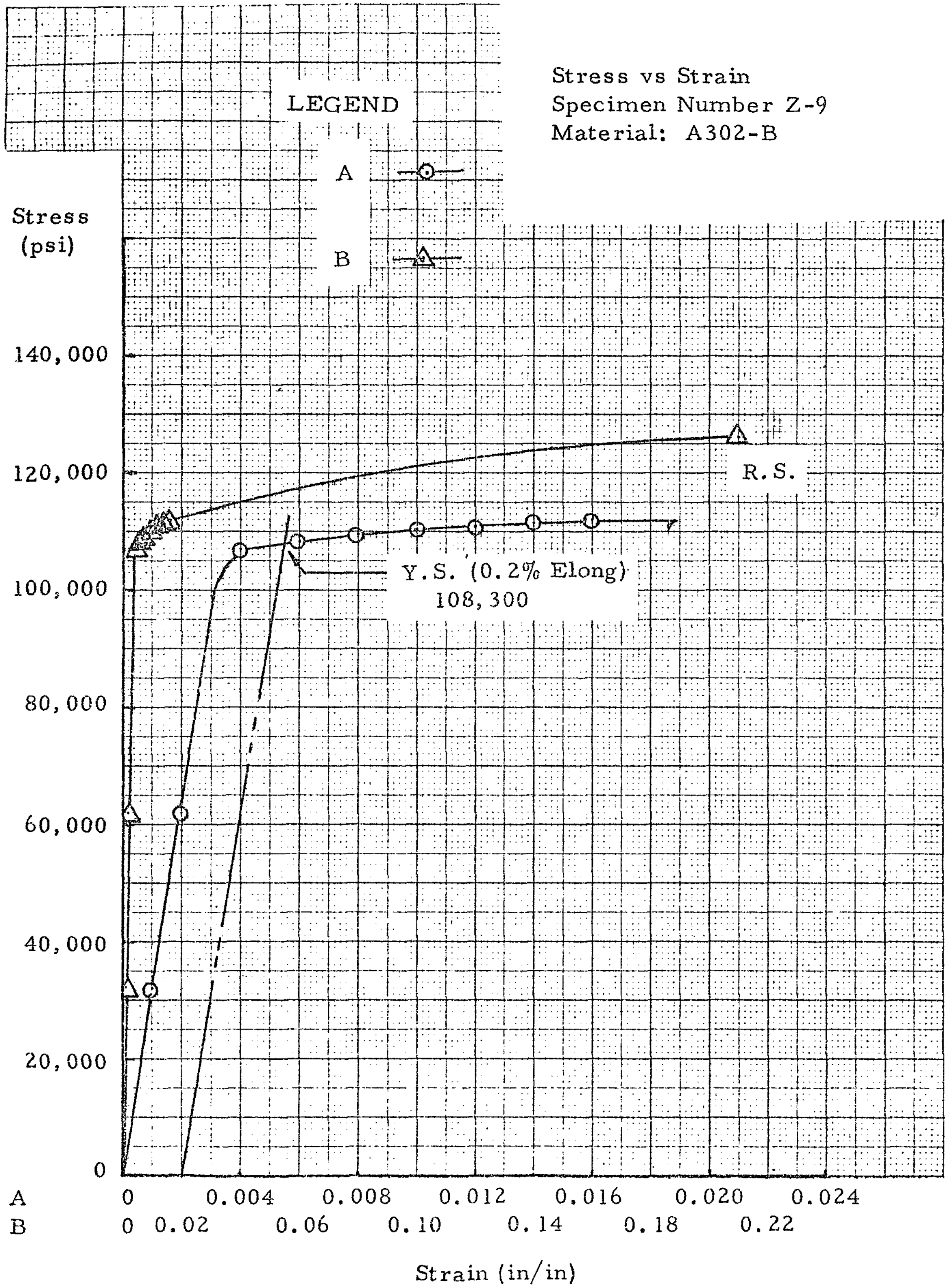


Figure C-36. Stress vs Strain, Specimen Number Z-9

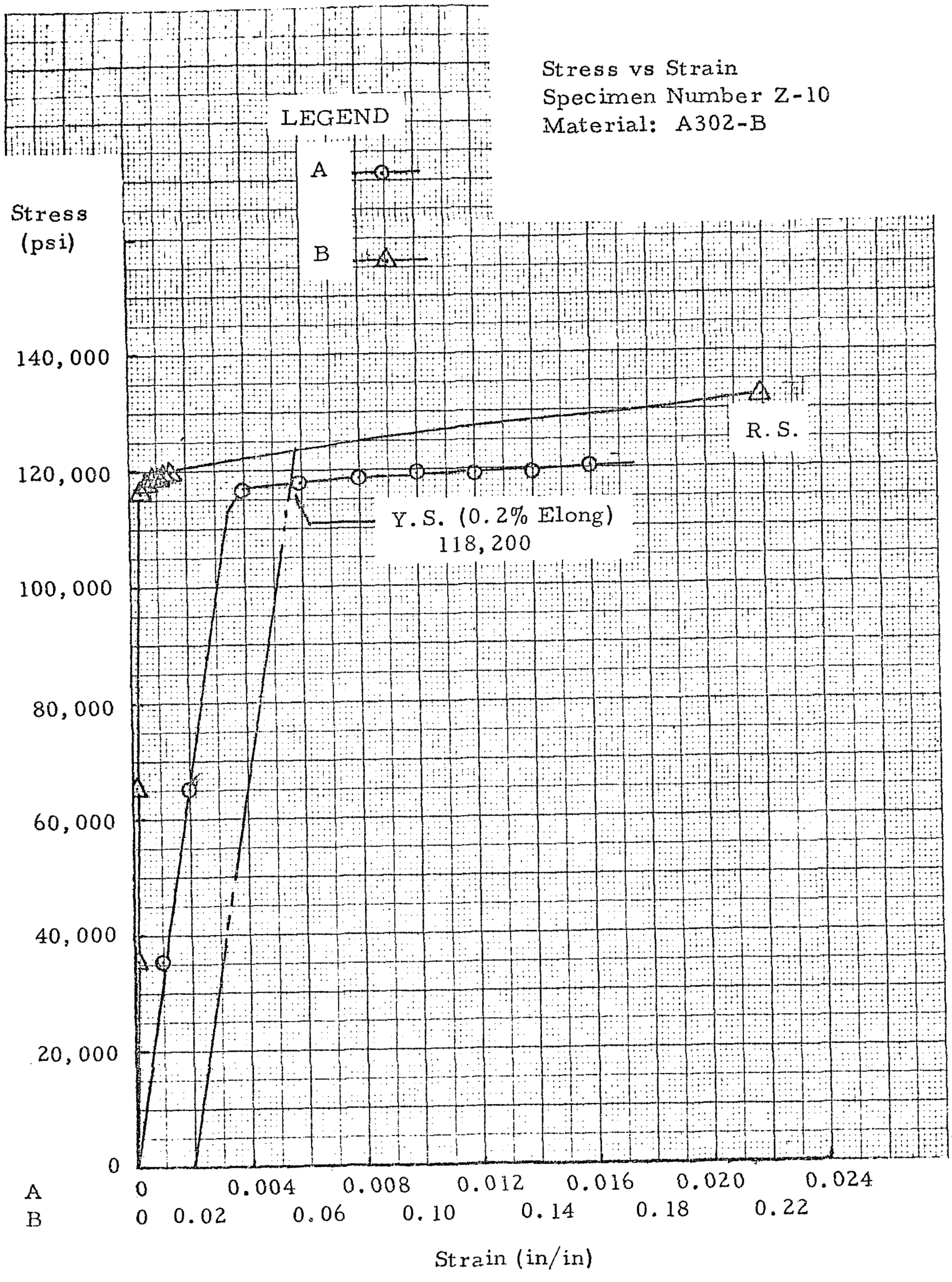


Figure C-37. Stress vs Strain, Specimen Number Z-10

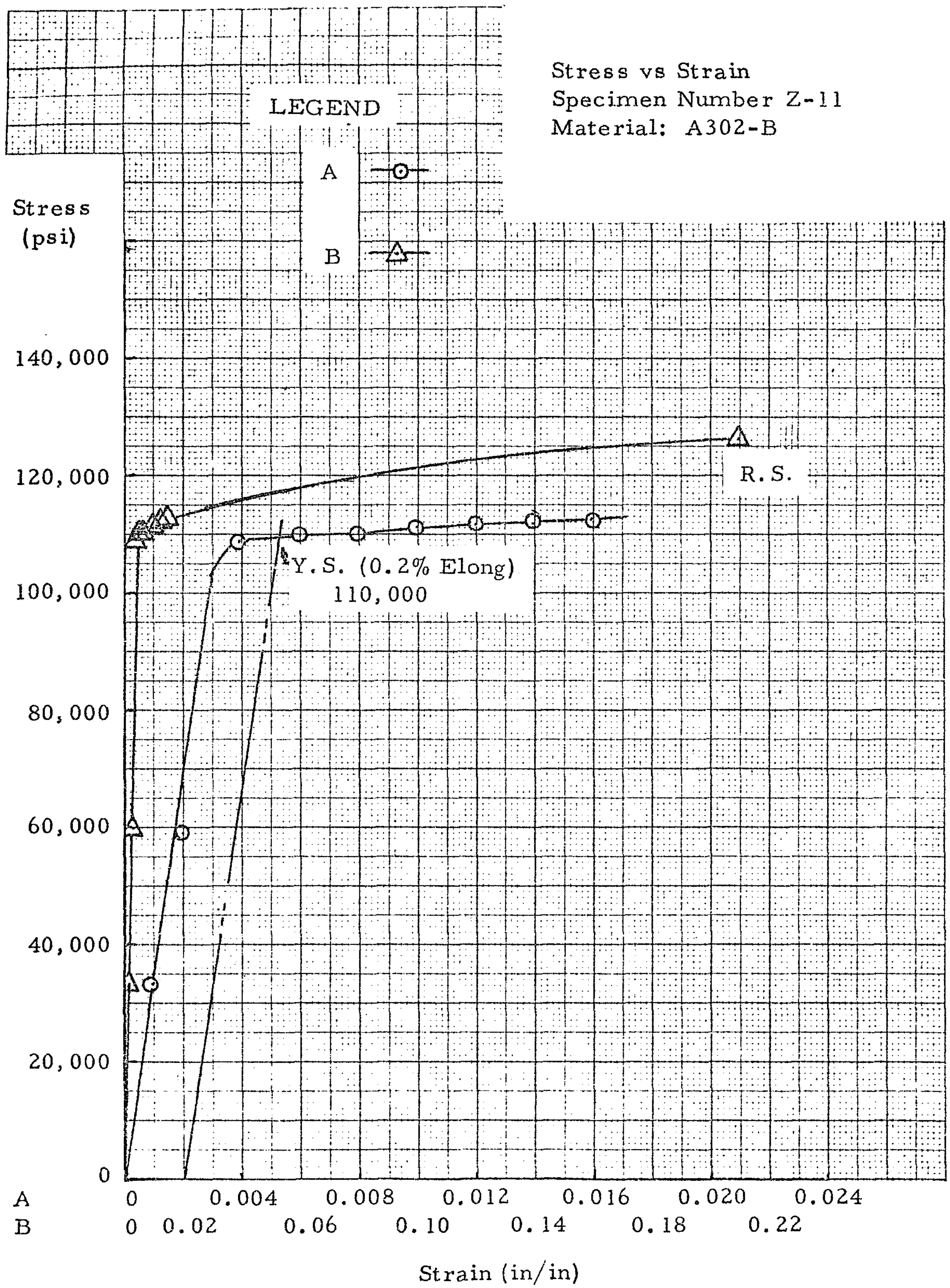


Figure C-38. Stress vs Strain, Specimen Number Z-11

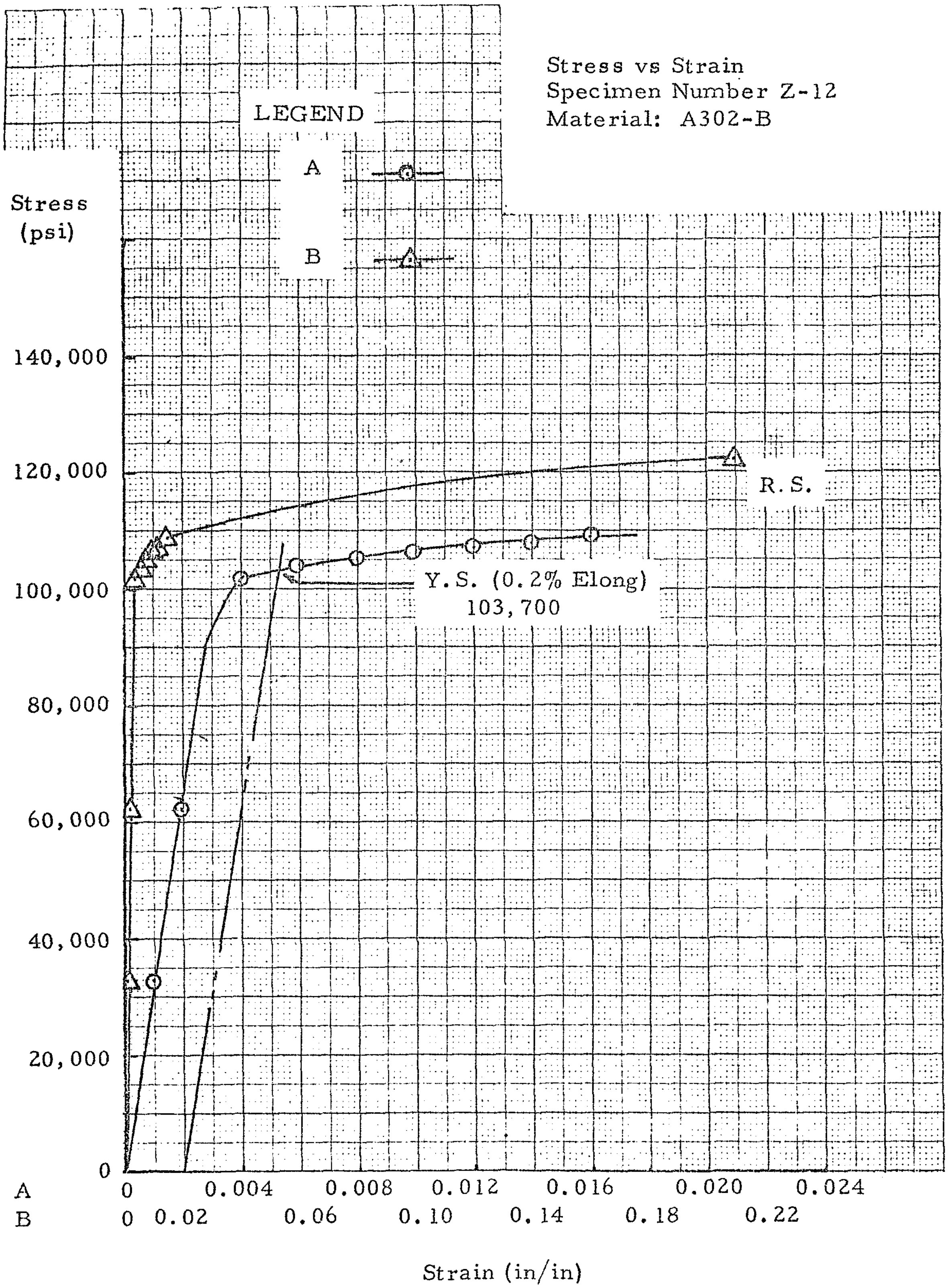


Figure C-39. Stress vs Strain, Specimen Number Z-12

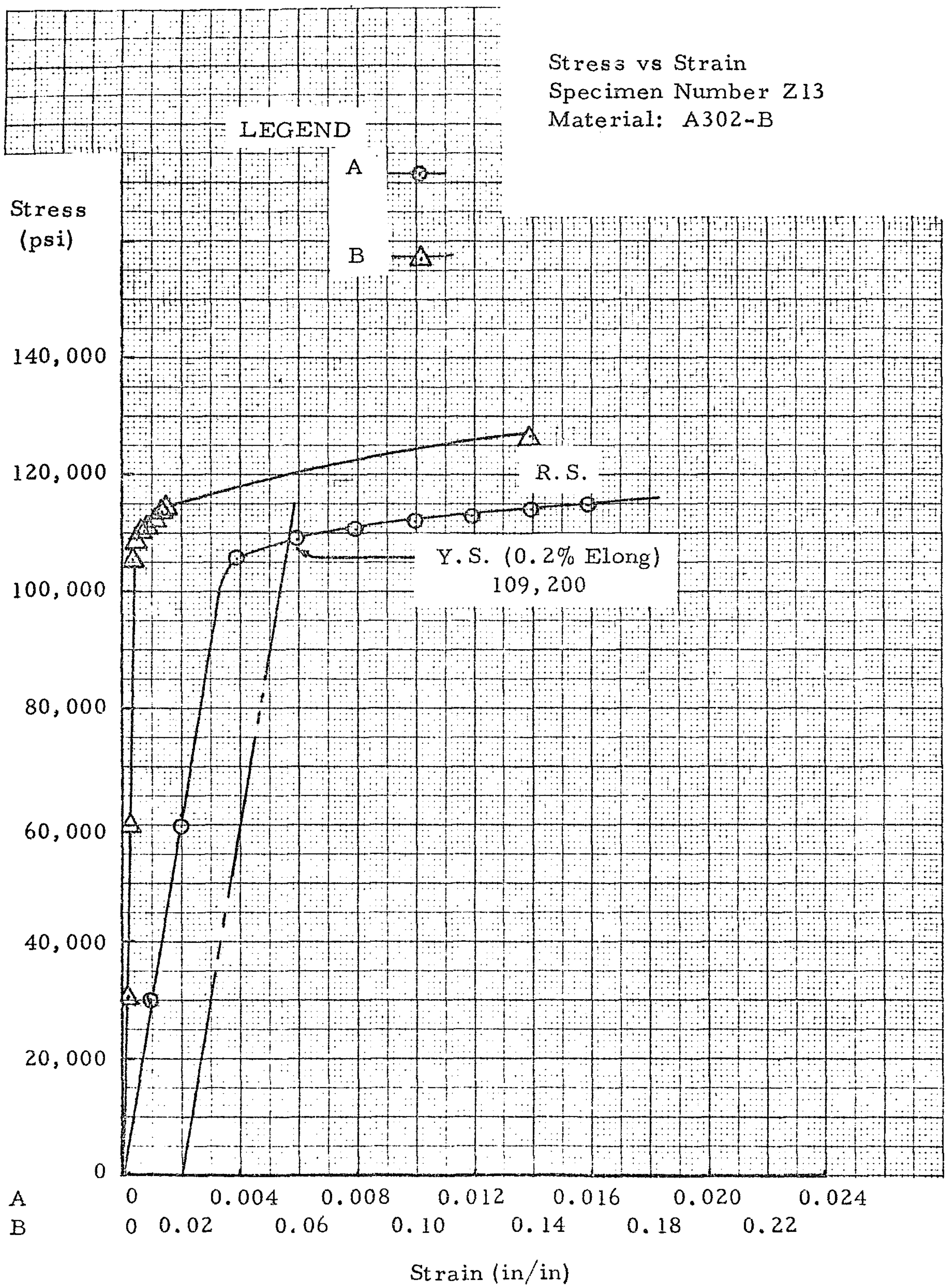


Figure C-40. Stress vs Strain, Specimen Number Z-13

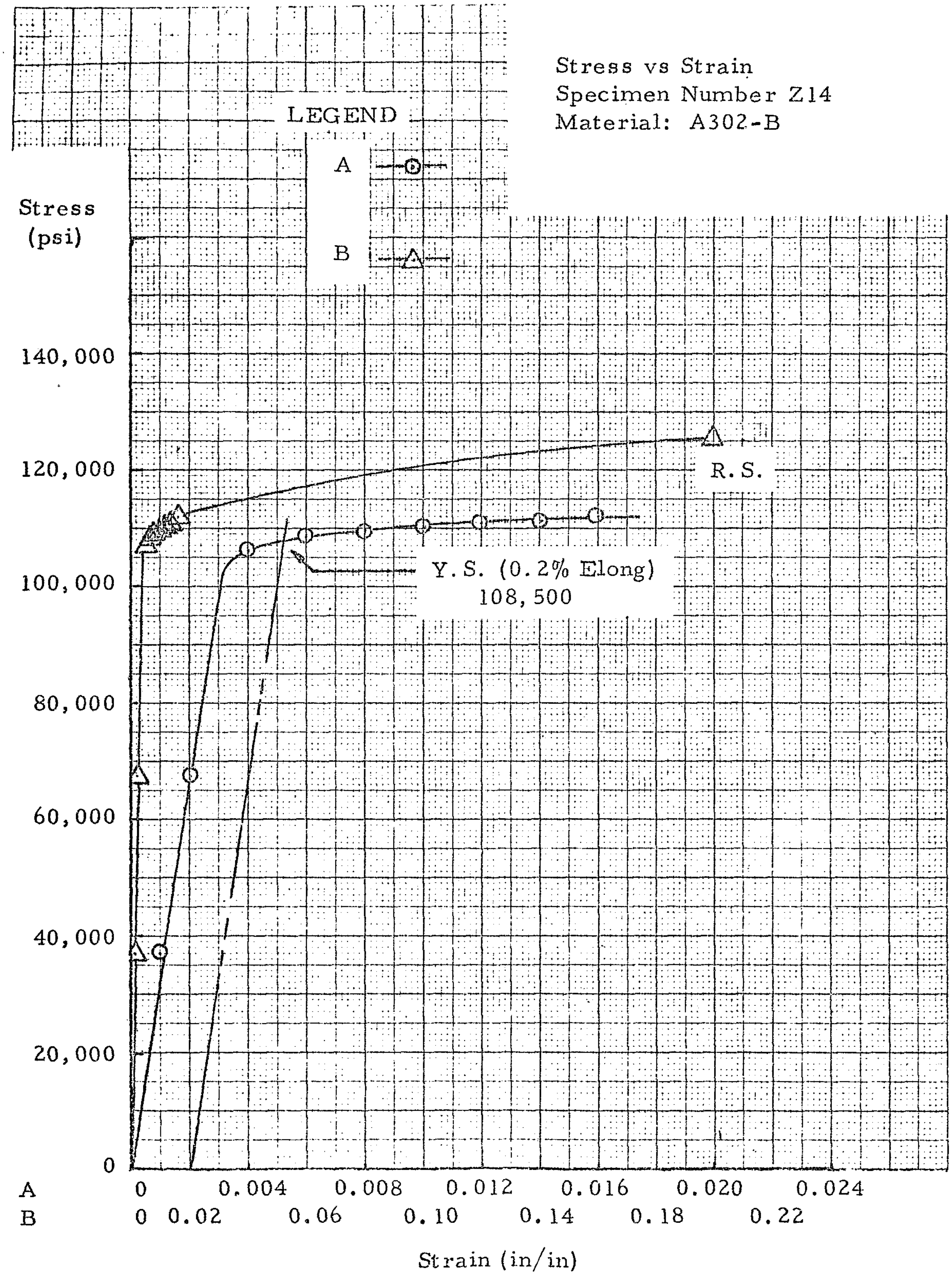


Figure C-41. Stress vs Strain, Specimen Number Z-14

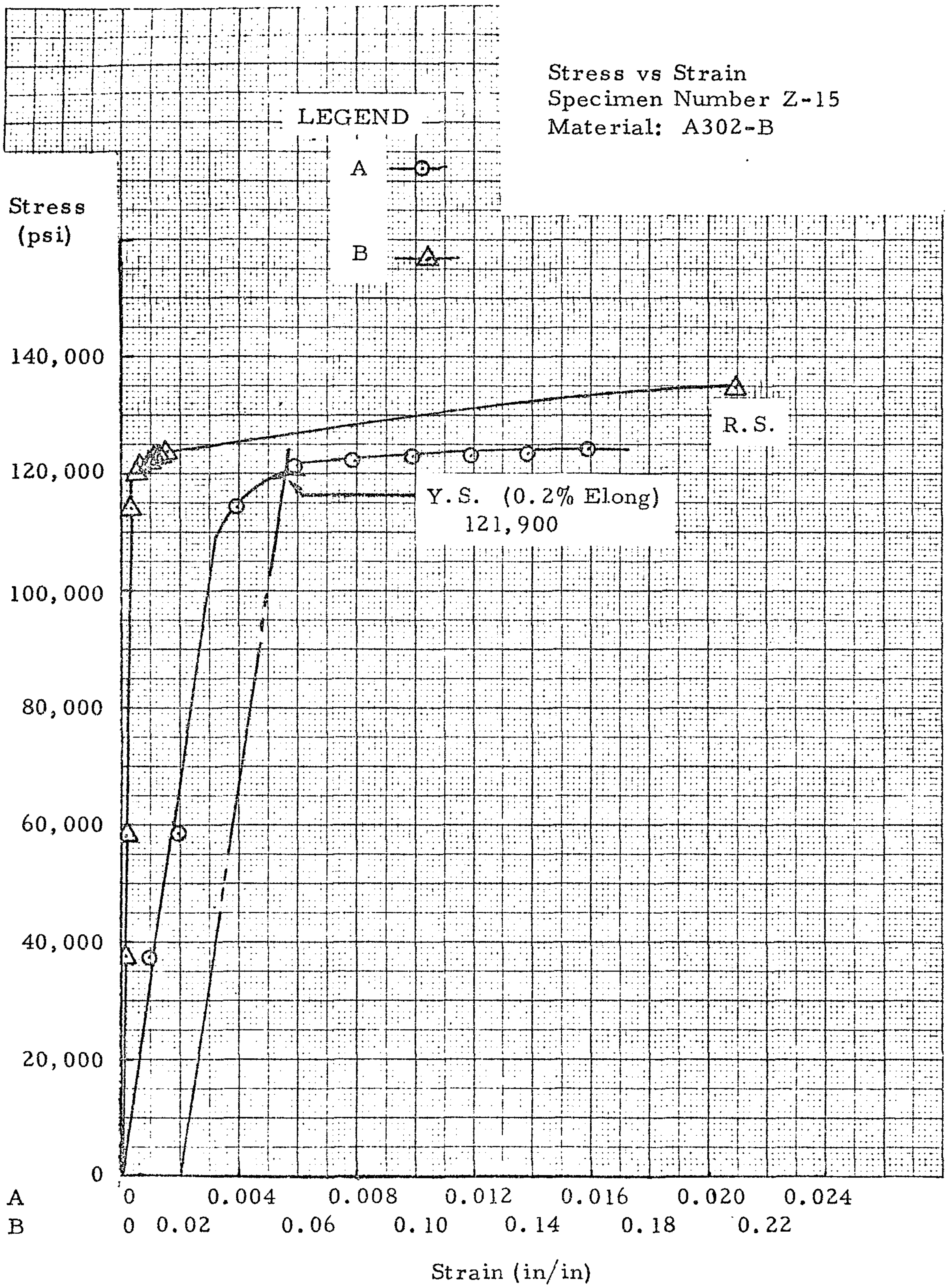


Figure C-42. Stress vs Strain, Specimen Number Z-15

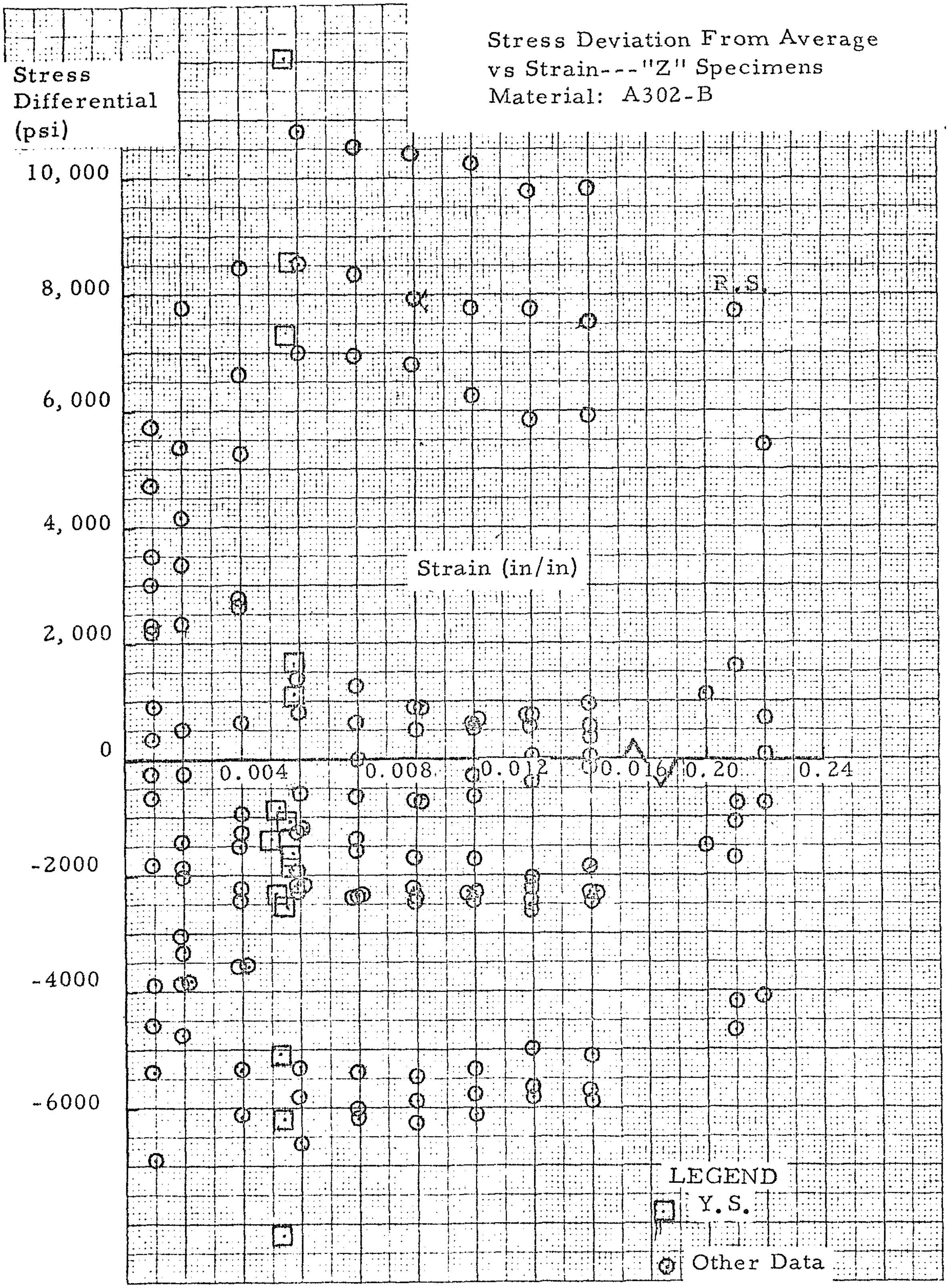


Figure C-43. Deviation From Average Stress vs Strain for Z Specimens

APPENDIX D

A HISTORY OF SOME HYDROGEN PRESSURE VESSEL FAILURES

1. Hydrostatic tested to 10,080 psig before being placed in service.

2. Pressurized with GN_2 to 6000 psig for 1 or 2 days in January 1966.

3. Held with GN_2 at 5800 psig for 2 or 3 days.

4. Held with GN_2 at 4500 psig for 2 or 3 days.

5. Pressure decreased to 0 psig during a blow-down about the middle of February.

6. Pressurized with GH_2 to 3000 psig on 19 February and held for 2 or 3 days.

7. Pressure increased to 3500 psig GH_2 with resultant leakage in the valves and piping.

8. Pressure increased to 4000 psig GH_2 and held until 3 March 1966.

9. GH_2 pressure increased to 5300 psig on March 3, 1966.

10. Discovered the GH_2 to be contaminated and emptied vessel on 4 March 1966.

11. Refilled with GH_2 and pressurized straight up to 5850 psig on 6 March 1966 and vessel leaked immediately from vent ports on both ends of vessel.

A History of Some Hydrogen Pressure Vessel Failures

A. Hydrogen Vessel Failures at Aerojet General Corporation:

Aerojet General Corporation (AGC) experienced failures of 1300 cu. ft., 5000 psig GH_2 storage vessels. AGC has seven vessels in service at 5000 psig, four containing hydrogen and three containing nitrogen. Three failures have occurred in the 1-inch nozzles in hydrogen - containing vessels manufactured by A. O. Smith using A. O. Smith material (similar to A302B Ni modified). These nozzles were welded into the approximately 6-inch thick pressure vessel wall with a 1-inch weld surrounding the nozzle. The weld was not stress relieved and because of the multi-layer design of the pressure vessles, numerous stress raisers at the weld must be assumed to exist. These failures occurred at pressures of around 4.300 to 4,400 psig.

A failure analysis was made on only the last of the three failures. The failure was apparently initiated at the nozzle-weld interface and propagated in a partially ductile, partially brittle manner through the nozzle. The weld nozzle materials were found to be essentially free of defects and to have good mechanical properties. This failure analysis indicated that the internal stresses in the nozzle were a large fraction of the yield strength of the material. AGC investigators believe that the failures occurred as a result of the combined effect of local high stress and hydrogen embrittlement.

Aerojet General also has three laminated vessels fabricated from T-1 steel by the Struthers Wells Corporation. One leaked after being used in HP hydrogen service. The vessel was opened and severe cracking was found in the longitudinal seam welds of the vessel. Inspection of the other two vessels before use, however, revealed similar but less severe cracks in some of the weld zones of these vessels. This would indicate that poor fabrication as well as the hydrogen service contributed to this failure.

B. Hydrogen Vessel Failure at MTO:

One of the three hydrogen vessels (1300 cu. ft.) at MTO developed a leak on 6 March 1966. These Struthers Wells Vessels are made of ASTM A-514-64 (T-1), which is difficult to weld properly and were designed for 6300 psig WP GH_2 service. The sequence of events which transpired up to the time of failure was as follows:

APPROVAL

TR-451

TEST REPORT

HYDROGEN EMBRITTLEMENT TESTS

OF

PRESSURIZED CYLINDRICAL AND

TENSILE SPECIMENS

INCLUDING

CONVENTIONAL TENSILE TESTS

ON

ASTM A-302-B STEEL, NICKEL MODIFIED

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